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CONTACT ORE DEPOSITION AT THE CALUMET IRON MINE, COLORADO.[1]

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INTRODUCTION.

SINCE the pioneer work of von Groddeck and of Vogt two questions relating to contact metamorphism have been of outstanding interest—the causes for localization of the ores and the mineral paragenesis in the contact halo. These form the central themes of the classic regional studies of Goldschmidt at Kristiania, Norway,[2] and of Barrell at Marysville, Montana.[3] Arising from these, are two other questions of importance to the economic geologist, namely, what are the age relations of the ore minerals to the other components of the metamorphic aureole, and, if the ore minerals are younger, are they localized in preexisting openings that resulted from volume shrinkage after the formation of the metamorphic silicates. A close study of the work of Leith and Harder at Iron Springs,[4] suggested that both of these questions should be answered in the affirmative, though evidence is not conclusive and the observed features are subject to alternative explanations, at least in detail, as will appear below.

With this background, the detailed study of the abandoned iron mine at Calumet, Chaffee County, Colorado, offered an at-

[1] Presented before the Geological Society of America, December 29, 1933.

[2] Goldschmidt, V. M.: Die Contactmetamorphose im Kristiania gebiet. Skrift. Videnskap., Kristiania, Norway, 1911.

[3] Barrell, Joseph: Geology of the Marysville Mining District, Montana: A Study of Igneous Intrusion and Contact Metamorphism. U. S. Geol. Surv. Prof. Paper 57, pp. 1–178, 1907.

[4] Leith, C. K., and Harder, E. C.: The Iron Ores of the Iron Springs District, Utah. U. S. Geol. Surv. Bull. 338, esp. pp. 66–70, fig. 10 (p. 71), and pp. 85–86, 1908.

tractive opportunity. For proper grasp, an areal geologic map was first prepared; then the accessible parts of the iron deposit were examined. This field work consumed four weeks in August, 1933.

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Earlier Publications.—A report on the Calumet Mine, dated 1892 and written by R. C. Hills, was made available through the courtesy of the Colorado Fuel and Iron Company. In 1931, Butler and Goddard prepared a reconnaissance geological map, which was later incorporated in the new geologic map of Colorado.[5] Other than these, nothing detailed has been written on the geology of this interesting deposit.[5a]

LOCATION OF DISTRICT AND ACCESS.

The Calumet mine is located in T. 51 N., R. 9 E., Chaffee County, central Colorado. Its geographic position is shown in Fig. 1. The nearest settlement is the little gold mining town of Turret, now almost deserted. A good secondary road leaves the Salida-Leadville highway and passes up the gorge of Ute Creek. From this road branches lead northwest past the stone quarry in the northwest quarter of Section 35, west and north to the

[5] Geologic map of Colorado: U. S. Geol. Surv., 1935.

[5a] Burbank, W. S., and Lovering, T. S.: Relation of Stratigraphy, Structure, and Igneous Activity to Ore Deposition of Colorado and Southern Wyoming. Ore Deposits of the Western United States, Amer. Inst. Min. Met. Eng., Lindgren Vol., pp. 290, 294, 1933.

Calumet mine, and farther west to Turret. The main road from Whitehorn southwest to Salida now follows the first-mentioned of these three roads.

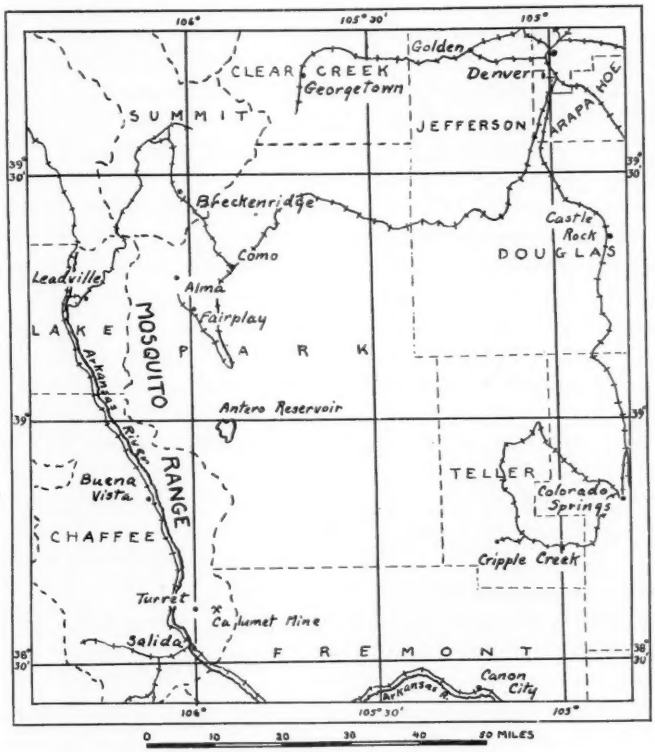

FIG. 1. Sketch map to show location of Calumet iron mine, Chaffee County, Colorado.

A railroad spur once connected the Calumet mine with the main line of the Denver and Rio Grande Western Railroad via the valley of Fleming Creek, but was dismantled since the closing of the mine in 1900.

GENERAL GEOLOGIC SETTING.

Physiographic Features.—The area in which the Calumet mine is situated is in the foothills that are the southward end of the Mosquito Range. South and west is the Arkansas Valley. The Calumet district is in rolling upland with an irregularly hilly topography and a relief of as much as 2,000 feet. The higher topography generally is characterized by the presence of resistant grits and sandstones, Tertiary intrusions, and ancient crystallines. In detail, hogbacks and monument-like erosion remnants are characteristic.

Several summits at about 10,200 feet, such as Greentop Mountain, seem to preserve remnants of a rolling upland, believed to be correlative with the 12,000-foot benches farther north near Leadville.[6] Below these are wide shoulders at 9,150–9,350 feet altitudes, and occasional strikingly flat "parks," locally a square mile or more in extent and having altitudes of 8,900 feet in the more conspicuous cases, probably corresponding to the 10,000-foot valley benches at Leadville [7] and the 6,800-foot surface along the Royal Gorge of the Arkansas;[8] they are a striking feature of the immediate region and are believed to be of early Pliocene age. At still lower altitudes, approximating 8,600 feet, are stream floodplains, probably of Pleistocene age, and these in turn have been trenched to depths of 10 or 15 feet or more as a result of recent rejuvenation.

There is no record of glaciation in the immediate region and only weathering products and alluvial deposits cover the bed rock, which is largely well exposed.

Stratigraphic Succession.—The sequence in the neighborhood of the Calumet mine is briefly given in Fig. 2. A good general description of the regional succession, applicable to this area, is

[6] Behre, C. H., Jr.: Physiographic History of Upper Arkansas and Eagle River. Jour. Geol., vol. 43, pp. 808–812, 1935.

[7] Behre, C. H., Jr.: Physiographic History of the Upper Arkansas and Eagle Rivers, Colo. Jour. Geol., vol. 41, pp. 795–797, 800–801, 1933.

[8] Powers, W. E.: Physiographic History of the Upper Arkansas River Valley and the Royal Gorge, Colorado. Jour. Geol., vol. 43, pp. 190–191, 195–196, 199, 1935.

that of Johnson,[9] based mainly on studies made near Leadville and Alma. The pre-Cambrian rocks are not near the areas of mineralization here described, for they lie chiefly a quarter of a mile or so to the west. Conspicuous in the section are the almost

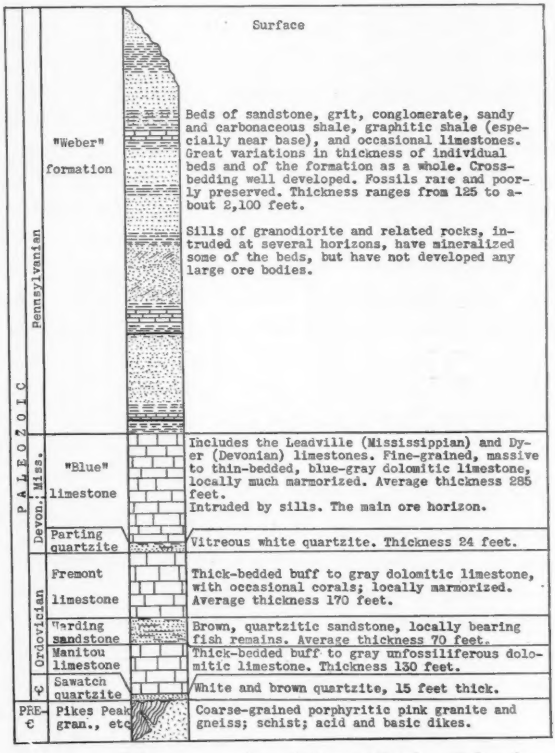
Surface
PALEOZOIC
Pennsylvanian
"Weber" formation
Beds of sandstone, grit, conglomerate, sandy and carbonaceous shale, graphitic shale (especially near base), and occasional limestones. Great variations in thickness of individual beds and of the formation as a whole. Cross-bedding well developed. Fossils rare and poorly preserved. Thickness ranges from 125 to about 2,100 feet.
Sills of granodiorite and related rocks, intruded at several horizons, have mineralized some of the beds, but have not developed any large ore bodies.
Devon.-Miss.
"Blue" limestone
Includes the Leadville (Mississippian) and Dyer (Devonian) limestones. Fine-grained, massive to thin-bedded, blue-gray dolomitic limestone, locally much marmorized. Average thickness 285 feet.
Intruded by sills. The main ore horizon.
Parting quartzite
Vitreous white quartzite. Thickness 24 feet.
Ordovician
Fremont limestone
Thick-bedded buff to gray dolomitic limestone, with occasional corals; locally marmorized. Average thickness 170 feet.
Harding sandstone
Brown, quartzitic sandstone, locally bearing fish remains. Average thickness 70 feet.
Manitou limestone
Thick-bedded buff to gray unfossiliferous dolomitic limestone. Thickness 130 feet.
Sawatch quartzite
White and brown quartzite, 15 feet thick.
PRE-Є
Pikes Peak gran., etc.
Coarse-grained porphyritic pink granite and gneiss; schist; acid and basic dikes.

FIG. 2. Columnar section, Calumet district, Colorado.

total absence of the Sawatch quartzite, which is much thicker farther north, and the great thickness of the Weber (?) formation. The presence of distinguishable Harding sandstone and

[9] Johnson, J. H.: Paleozoic Formations of the Mosquito Range, Colorado. U. S. Geol. Surv. Prof. Paper 185–B, esp. pp. 17–19, 1934.

Fremont limestone, absent in much of the adjacent region, though present at Trout Creek, 25 miles north,[10] is also striking. A comparison of the Calumet section with that at Canyon City [11] and those given by Johnson shows that the Harding and Fremont both thicken gradually from Trout Creek southward and eastward.

It did not prove feasible to separate the Devonian Dyer limestone from the overlying Mississippian Leadville limestone in the field and these two similar formations are therefore lithologically mapped together under the old name of "Blue" limestone.

The "Weber" formation varies abruptly in thickness in adjacent sections due to differences in the amount included between its base and the sills of Tertiary age to be mentioned below; thus, on Porphyry Hill, half a mile north of the Calumet mine, the "Weber" appearing between the top of the "Blue" limestone and the base of the overlying sill is 150 feet thick, whereas it is over 2,000 feet about a mile and a half farther south. Occasional limestone lenses occur in the "Weber." The lowest part of the formation is more shaly and carbonaceous than the upper, and bears two or possibly three highly carbonaceous horizons each 3 feet thick, readily graphitized by contact metamorphism. The lowest of these is within 20 feet of the base of the "Weber"; a second is 150 feet above the base.

Calumet Granodiorite.—An irregular mass of granodiorite, with local differentiates, has been intruded into the Paleozoic rocks in the neighborhood of the Calumet mine. Some idea of its extent may be obtained from the geologic map (Fig. 3) and from the fact that the outer limits of the mass as traced by the authors indicate that it forms the surface rock for at least 32 square miles, and for another 12 square miles it appears to be covered only by late Tertiary lava flows.[11a] The Calumet mine is situated half a mile west of the west-central edge of this mass and

[10] Johnson, J. H.: *Op. cit.*, pp. 22 and 23.

[11] Walcott, C. D.: Preliminary Notes on the Discovery of a Vertebrate Fauna in Silurian (Ordovician) Strata. Geol. Soc. Am. Bull., vol. 3, pp. 153–172, 1892.

[11a] No attempt is here made to distinguish the smaller branch intrusion, designated the Calumet stock, from the larger body of which it is either a part or an apophysis and which has been called by Burbank (*op. cit.*) the Whitehorn stock.

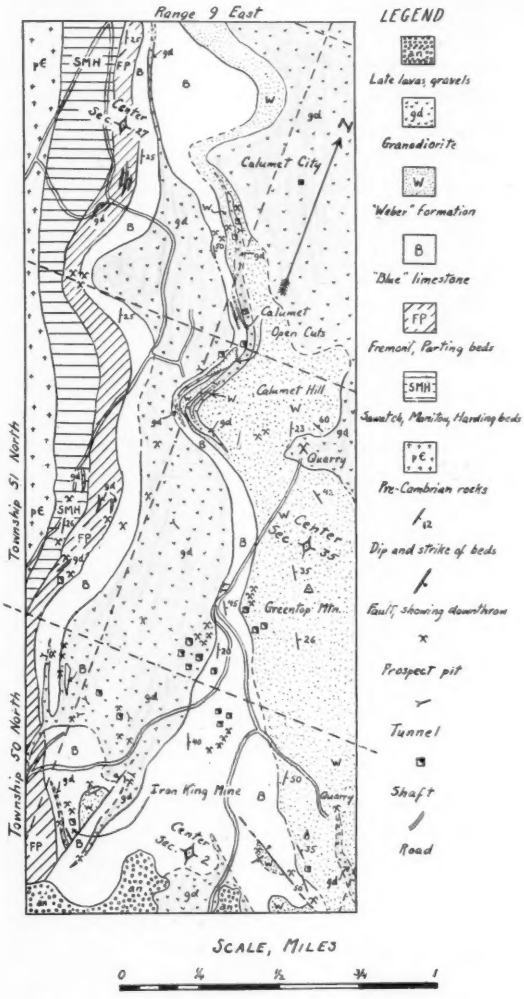

FIG. 3. Geologic map of the Calumet district, Colorado.

dikes and sills project out from the main plug across the Paleozoic rocks on its western border.

Hand specimens show a gray medium-grained crystalline rock, generally equigranular, and with crystals unoriented, but locally trachitoid to gneissic. Where the texture is gneissoid there are no megascopically continuous differentiated bands; instead there is only the parallel elongation of particles suggesting flow lines. Where massive, the rock weathers in irregular knobs, but where it is gneissoid or trachitoid, it splits, on weathering, into flat slabs. This peculiar texture is characteristic of the periphery of the mass; in the central part of the main body, on the other hand, the rock is massive and has, in fact, been successfully quarried as a building stone under the name of "granite."

Inclusions are also common in the outer parts of the intrusion. They are in part basic flattened pebbles, unusually rich in biotite and chlorite; such pieces are generally elongate, suggesting slabs of engulfed shale, now altered; their elongation is parallel to that of the crystals of the igneous rock. Another type of inclusion is suggested by oval cavities, up to 10 inches in diameter, lined with crystals of dolomite; these cavities suggest the former presence of carbonate-rich rocks. A third type consists of what appears to be a metamorphosed sandstone or quartzite, the edges of the fragments being generally rounded and grading into the enclosing igneous rock. All three kinds of inclusion suggest fragments torn from the surrounding sediments—the more basic and most of the sandy inclusions coming from pre-Cambrian schist or the shaly and sandy beds of the "Weber," whereas the carbonate inclusions came presumably from the Paleozoic limestones. No very careful observations were made, but cursory examination of the rock structures gave no clue as to the direction of magma movement.

Several differentiated bodies and satellite dikes were distinguished within the intrusive, but are not separately shown on the geologic map. A white, quartz-feldspar pegmatite rich in large biotite crystals appears within the main intrusive mass on top of Corundum Knob (S. E. ¼, sec. 22, T. 51 N., R. 9 E.); another

outcrops on Calumet Hill above the mine. Locally there are also aplites and granitoid dikes and irregular masses up to 120 feet in diameter; one such can be seen near the former site of Calumet City. Basic differentiates of smaller size occur locally, some as small dikes, others with the irregular, stock-like form commonly assumed by intrusions of the aplite and pegmatite types; a dike of basic composition may be seen just south of the quarry located in the northwest quarter of Section 35. Acid porphyry dikes occur locally as well, scattered through the sedimentary areas.

In composition the rock varies slightly from place to place. Detailed petrographic studies by one of us (Osborn) show the following constituents: plagioclase 45–50%; quartz 10–25%; orthoclase 15–18%; biotite 8–10%; hornblende 4–7%; magnetite 1–15%; augite 1%; titanite 1%. The plagioclase is zoned, and ranges in composition from labradorite to andesine. Small amounts of primary apatite are present. There are also still smaller quantities of chlorite, epidote, antigorite, kaolin, uralite, and sericite. These six minerals, although present in the apparently unaltered rock, are looked upon partly as hydrothermal, partly as the result of reaction with the sediments. Among the strictly primary constituents, orthoclase, quartz, and (for the most part) magnetite are not euhedral and are regarded as later than the plagioclase, apatite, and ferromagnesian minerals.

Near its margins the rock is richer in augite; more centrally it bears relatively more hornblende. In all cases the augite shows a tendency toward conversion to uralite, however.

It will be inferred from the above that the average composition of the Calumet intrusion ranges from quartz monzonite to granodiorite. This composition is somewhat different from that of most of the large intrusive masses farther north in the Mosquito Range [12] and in the Sawatch Range directly west, across the Valley of the Arkansas.[13] Local occurrences of rocks similar to the

[12] See, for example, Emmons, S. F., Irving, J. D., and Loughlin, G. F.: Geology and Ore Deposits of the Leadville Mining District, Colo. U. S. Geol. Surv. Prof. Paper 148, pp. 46, 48, 50, 51, 1927.

[13] Crawford, R. D.: A Contribution to the Igneous Geology of Central Colorado. Am. Jour. Sci., 5th ser., vol. 7, pp. 367–368, 1924.

Calumet intrusion have been described, however, from the Alma district in the Mosquito Range [14] and from the Monarch-Tomichi district in the Sawatch Range,[15] though these granodioritic types occur in far smaller amounts than the more acid, monzonitic facies.

Two explanations may be offered for the more basic border and the more acid central mass observed in the Calumet intrusion.[15a] (1) The border may be regarded as rapidly cooling, and the central and main mass cooled more slowly. As a result of this contrast, the reactions hypothesized by Bowen [16] might have taken place in the central part of the intrusion, whereas they were inhibited in the more rapidly chilled periphery. Although this explanation may well serve to account for the relationship between the constituent minerals, it does not take into consideration the somewhat anomalous appearance of so relatively basic a rock in a region where the dominant intrusions of corresponding age are almost everywhere more acid.

(2) An alternative hypothesis assumes that the magma was originally acid enough to be classed as a monzonite. Its more basic characteristics are assigned to assimilation of the calcareous Paleozoic sediments through which it passed. The texture and field relations both show the Calumet intrusion to have been largely transgressive, and hence prone to assimilate the rocks traversed. The pre-Cambrian rocks first encountered in its upward way are here chiefly monzonites, and were therefore not assimilable or, if assimilated, had no effect. Quartzites and sandstones are not conspicuous below the base of the "Weber," and this horizon is topographically higher than most of the intrusive contacts here discussed. Above the pre-Cambrian, however, cal-

[14] Singewald, Q. D., and Butler, B. S.: Suggestions for Prospecting in the Alma District, Colorado. Colo. Sci. Soc. Proc., vol. 13, p. 94, 1933.

[15] Crawford, R. D.: Geology and Ore Deposits of the Monarch and Tomichi Districts, Colorado. Colo. Geol. Surv. Bull. 4, pp. 76–77, 1913.

[15a] For a more general discussion, not specifically directed at the Calumet stock, see also Burbank, W. S., *op. cit.*, pp. 291, 311.

[16] Bowen, N. L.: The Reaction Principle in Petrogenesis. Jour. Geol., vol. 30, pp. 177–198, 1922.

careous sediments stand in a ratio of over five to one to the siliceous sediments. An increase in lime content might well have made the igneous mass basic, *after* which the reaction series postulated by Bowen might have been effective. This explanation, the writers believe, is more in accordance with the facts than a combination of the reaction principle and the assumption that the intrusion was, for no obvious reason, more basic than is usual.

Relation of Intrusions to the Surrounding Rocks; Probable Age.—In the immediate neighborhood of the mine all of the intrusions of importance are of the type of the Calumet granodiorite and its differentiates. As implied above, the largest body of this rock in the district is stock-like. It cuts the "Weber" some distance east of the Calumet mine (Fig. 3) and the contact is so irregular as to show clearly that the main mass is not in the form of a sill; indeed, in the northwest quarter of Section 35 an apophysis of the granodiorite extends westward so far into the "Weber" as to bring it almost down to the contact between the "Blue" limestone and the "Weber"; from Calumet Hill northward, however, this mass has essentially a sill-like relation. Thus, the inference is warranted that the plug east of the mine served as a feeder for a great sill, as well as for other similar bodies.

The other large body is a true sill lying within the "Blue" limestone west of the mine (Fig. 3). This body appears as a very thin sill in the west center of the northeast quarter of Section 27; thence southward it swells rapidly to a thickness of 450 feet due west of the Calumet mine, and then thins again southward, with some irregularities. Near its southern extremity it sends out transgressive apophyses from which small sills are intruded along the bedding; here blocks of limestone are included in it.

Several smaller sills are known in the neighborhood of the Calumet mine, but only one of these merits mention. It lies just east of the open cut at the mine, and is approximately 50 feet thick. At the mine it follows exactly the contact between the "Blue" limestone and the basal "Weber" shales, but both north-

ward and southward it rises stratigraphically so as to be 50 feet up in the "Weber."

The regional evidence favors assigning the intrusion of the granodiorite and its differentiates to the same time as the quartz monzonite stocks of this part of Colorado,—to the early Eocene.

Structure.—The regional structure is essentially monoclinal and remarkably simple. The beds strike generally N. 10–20° W., with an average dip of 20–30° E., but with local steepening. There are only three noteworthy departures from this general pattern. One of these is very near the western border of the granodiorite stock, in the north-central part of Section 35. Here, the dip of the bedding in the "Weber" steepens in such a way as to suggest, at least locally, the doming effect of the intrusive mass upon the adjacent sediments.

The other structural features that merit attention are two faults about 1½ miles south of the Calumet mine, one in the west half, the other in the northeast quarter of Section 2, T. 50 N., R. 10 E. The faults trend respectively N. 15° E. and N. 60° W.; the straightness of their courses suggests a vertical dip; in both instances the west side is downthrown.

CONTACT METAMORPHISM AND CONTACT METAMORPHIC ORE DEPOSITS.

Economic interest centers around mineralization of the contact metamorphic or pyrometasomatic type. What follows is a generalized picture of this feature for the region as a whole, and a detailed account of its appearance in the Calumet mine. Ore deposition and contact metamorphism, being closely associated, are considered together. It should be noted that the picture is not complicated by any dynamic metamorphism.

Metamorphism of Clastic Sediments.—The "Weber" sandstone shows considerable recrystallization of the quartz to the point of suturing of the grains, but no dense quartzite is developed. Some plagioclase, orthoclase, and biotite are also seen, but the forms of the grains suggest that these are primary (sedimentary) minerals. Wavy stringers of fibrolite may also be

observed in some layers near the intrusion. Other sandstones show similar alteration. All such changes are only noteworthy near the intrusions, however.

The non-carbonaceous shaly beds of the "Weber" are locally metamorphosed. They are baked and hardened and contain sillimanite and andalusite and possibly some cordierite. Pyrite is locally present, and the fine grains of plagioclase found here and there in the metamorphosed shales may also be of metamorphic origin.

In the lower part of the "Weber" formation there are highly carbonaceous shales which were also originally conspicuously calcareous. These have been altered by contact metamorphism to a fairly pure graphite. Such graphitic beds have been worked on a small scale, through inclined shafts or pits. The only conspicuous impurity in beds of this kind is calcite, which occurs in veinlets formed by deposition after metamorphism.

Metamorphism of Limestones.—As usual, the most striking changes are in the calcareous beds and here bleaching is the first sign of metamorphism, being conspicuous as much as half a mile from the nearest igneous rock. Bleaching is best seen in some of the layers of the "Blue" limestone, the original blue-gray color of which is in especially strong contrast to the glittering white of the altered rock,—much like the changes at Bingham.[17]

Marmorization is a common feature and is noted at points at least half a mile from the nearest outcrop of igneous rock. It generally goes with bleaching; in fact, there is a strong suggestion from the close association of the two, that bleaching without recrystallization is impossible. Marmorization is especially conspicuous in the Fremont limestone, possibly because of its greater purity. Where the rock is marmorized the bedding is also accentuated, and partings parallel to the beds, but more closely spaced than the usual bedding plane partings, are developed. This parting suggests schistosity except for its relation to the bedding; indeed it may represent a variety of "load schistosity,"

[17] Hunt, R. N.: The Ores in the Limestones at Bingham, Utah. Am. Inst. Min. Met. Eng. Trans., vol. 70, pp. 878–883, 1924.

induced by the weight of the overburden but facilitated by the heat of the intrusion.

Typically yet nearer to the outcrops of the intrusion are two other alteration effects. In one, the limestone is characterized by diopside blades, which show vaguely by reflection on the fractured surface; in the other, needles of a light gray-green silicate, with optical properties very similar to those of tremolite, are conspicuous. These two facies are illustrated respectively by outcrops in the N. E. quarter of the S. E. quarter of Section 34 and in the southwest quarter of Section 35, T. 51 N., R. 9 E. Some interest attaches to the relative nearness of these two alteration facies to the intrusion. For the two occurrences mentioned, the *horizontal* distances from the large sill that underlies the Calumet mine are virtually identical; the significant difference appears to lie in their vertical distances from the sill. As the sill dips *under* the latter locality with a dip of 20°, but over the former with a dip of 25°, the tremolite would seem to be developed nearer the igneous mass; moreover, the tremolitized limestone would lie *above* the intrusion and thus be more subject to attack by solutions and vapors from the intrusive mass. These considerations, plus the greater degree of conversion from original limestone to the secondary silicate, suggest that the tremolite represents more intense alteration than the diopside, even although the opposite would be inferred from the composition of the two minerals.[18] However, Barrell has suggested that the progressive changes usually attending contact metamorphism convert diopside into amphiboles, at least when the solutions are ferruginous.[19]

The most intense alteration took place near the Calumet mine. Here diopside, epidote, garnet, brown and green biotite, rare wernerite, tremolite, and actinolite replace the former carbonate; moreover, magnetite, and in much smaller amounts, hematite, pyrite, and chalcopyrite replace these silicates as well as the carbonate country rock, or cut them in veinlets. The diopside occurs in two differing ways—as bands apparently representing selective

[18] Harker, Alfred: Metamorphism. Methuen and Co., London, 1932, pp. 85–86.

[19] Barrell, Joseph: Geology of the Marysville Mining District, Montana. U. S. Geol. Surv. Prof. Paper 57, p. 141, 1907.

replacement of beds, and as spheroidal masses up to a foot in diameter, composed of radiating blades. Epidote appears here also. Garnet is present, but in relatively small amounts. Biotite is irregularly distributed and usually relatively unimportant. Tremolite and actinolite are likewise not prominent in this region of intense alteration.

Among the silicates, special interest attaches to the epidote, which is found in part in small disseminated crystals replacing altered limestone, but in part as veinlets in a rock now too greatly altered to make the relations of the epidote wholly clear. The latter type of occurrence generally shows well terminated crystals, and side by side with these are equally well formed quartz crystals. Such relations suggest two generations of epidote. The epidote filling the fissures is perhaps considerably later than most of the minerals of the contact aureole, and essentially pneumatolytic, as first suggested by Barrell for similar epidote at Marysville.[20]

Detailed descriptions and comprehensive studies of mineral paragenesis in magnetite deposits of metamorphic origin are few indeed and those that are available contradict each other at least in part. At Cornwall,[21] Hanover,[22] Bingham,[23] and Southern Vancouver Island [24] magnetite, as well as the other ore minerals, seems to be late, when compared with most of the contact metamorphic silicates typical of the aureole. On the other hand, the magnetite of Shasta County, California,[25] and at least some of that at Daiquiri, Cuba,[26] is specifically described as earlier than

[20] *Op. cit.*: pp. 141–142.

[21] Callahan, W. H., and Newhouse, W. H.: A Study of the Magnetite Orebody at Cornwall, Pennsylvania. ECON. GEOL., vol. 24, pp. 407–409, 1929.

[22] Paige, Sidney: The Hanover Iron-Ore Deposits, New Mexico. U. S. Geol. Surv. Bull. 380, pp. 212–213, 1909.

[23] Winchell, A. N.: Petrographic Studies of Limestone Alterations at Bingham. Am. Inst. Min. Met. Eng. Trans., vol. 70, pp. 897–898, 899, 1924. The mineralization here, however consists preponderantly of sulphides instead of oxides.

[24] Clapp, C. H.: Southern Vancouver Island. Canada Geol. Surv. Mem. 13, pp. 162–163, 1912.

[25] Prescott, Basil: The Occurrence and Genesis of the Magnetite Ores of Shasta County, California. ECON. GEOL., vol. 3, p. 475, 1908.

[26] Lindgren, Waldemar, and Ross, C. P.: The Iron Deposits of Daiquiri, Cuba. Am. Inst. Min. Eng. Trans., vol. 53, p. 51, 1916.

the contact metamorphic silicates. At Iron Springs, Utah, the evidence cited is somewhat contradictory,[27] and much the same may be said of the Mackay, Idaho, district,[28] where veinlets of magnetite cut a garnetiferous contact halo but the garnet itself bears cores of magnetite. It is to be noted that a careful review of paragenesis is available in only one of the papers listed, that on the Cornwall deposits.

In the Calumet district the evidence is strong that, as compared with the silicates, magnetite was a late mineral in the contact aureole, and much the same may be said of pyrite, though it is present in far lesser amounts and therefore affords less evidence.

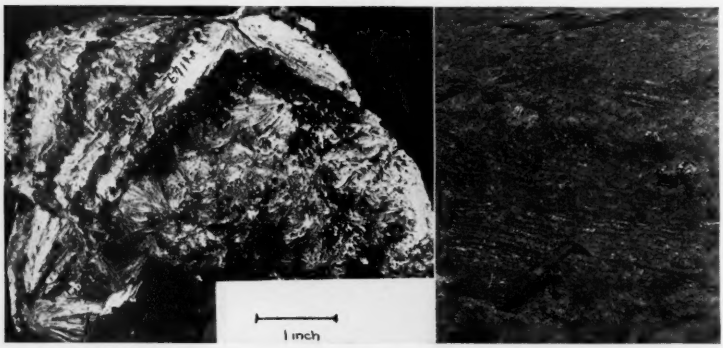

FIG. 4 (left). Magnetite filling in around sheaf-like aggregates of diopside, Calumet mine.

FIG. 5 (right). Magnetite (dark) and diopside (light) bands replacing limestone, east wall of north open cut, Calumet mine.

The chief silicate associated with the magnetite is diopside. Some of the magnetite actually occupies small veinlets that evidently resulted from the shattering of the diopside. Much of the magnetite fills in, in finely crystalline masses, at the ends of radiating sheaves of diopside (Fig. 4). And finally much of

[27] Leith, C. K., and Harder, E. C.: The Iron Ores of the Iron Springs District, Southern Utah. U. S. Geol. Surv. Bull. 338, pp. 78 and 85, 1908.

[28] Umpleby, J. B.: Geology and Ore Deposits of the Mackay Region, Idaho. U. S. Geol. Surv. Prof. Paper 97, p. 54, 1917.

the magnetite occurs interbanded with diopside (Fig. 5); megascopic evidence alone would not clearly show that the magnetite was latest in this last mode of occurrence, but the microscope establishes the late age of the magnetite (see Fig. 6).

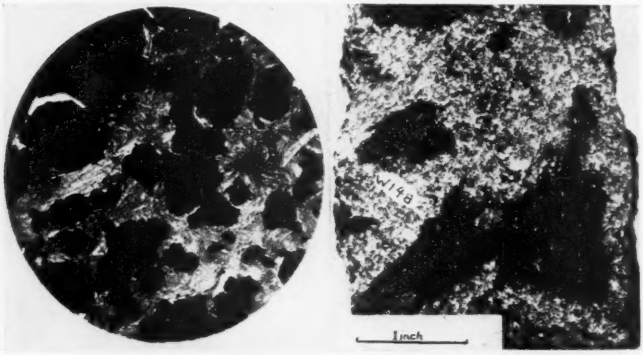

Fig. 6 (left). Magnetite "chinking" in around diopside and replacing the latter. Transmitted light; upper nicol not introduced. Enlarged 50 times.

FIG. 7 (right). Large augite crystals averaging one inch or more in length, associated with plagioclase and epidote in the endomorphosed phase of the diorite sill just east of the Calumet mine.

Since the greater part of the metamorphism and all of the iron ore deposition took place in the limestone, a brief summary of the mineral paragenesis in the contact metamorphic zone may here be presented as follows:

1. Calcite, from original limestone, recrystallized.
2. Diopside, epidote, and other silicates; probably in the order tremolite, diopside, epidote.
3. Magnetite and hematite, slightly as veins but chiefly in mass, as replacements.
4. Pyrite and chalcopyrite, largely as veins.
5. Calcite and quartz, chiefly in veins.

Endomorphism.—Within the granodiorite, notably near the large ore bodies of the Calumet mine, there was considerable metamorphism, so much so that along the eastern edge of the open cut it becomes impossible to tell whether a given spot is within the igneous rock or the metamorphosed sediment. The granodiorite is here heavily bleached; thus, the large uppermost sill at the mine is dark in color at the southern end of the south open cut, but rapidly changes northward to a light gray rock with a greenish cast, then blends into the adjacent limestone with a light olive-green color. With this change comes a disappearance of the primary femic minerals, and the preponderance of epidote, diopside, calcite, and a small amount of actinolite. The plagioclase in the intrusive, however, is altered but little, where attacked at all; calcite and epidote are the replacing minerals. Near the contact fibrous tremolite and especially coarse poikilitic augite crystals are conspicuous (Fig. 7).

THE CALUMET MINE.

Production and History.—The Calumet mine was operated almost continuously from 1882 to 1900 by the Colorado Fuel and Iron Company. The total recorded production through 1899 was 228,781 long tons. The tenor of the ore mined during early years of operation was high, but it steadily declined. Moreover, as depth was gained the ratio of sulphur increased, notably when the mining was continued below the water table, and the iron content sank from 60 per cent (typical of the tenor of 1887 or so) to 43–45 per cent (as in 1894). It was during this period that the little mining town of Calumet City was built up, housing at one time several hundred workers. In 1905, perfunctory explorations were undertaken to sample the remaining ore, but without favorable results.

Description of Workings.—The Calumet mine is at an altitude of about 9,500 feet, on a steeply sloping hillside in the southwest corner of Section 26 and the northwest corner of Section 35, T. 51 N., R. 9 E. Fig. 8 is a map of the surface workings of the mine. The underground workings are unmapped and are

FIG.

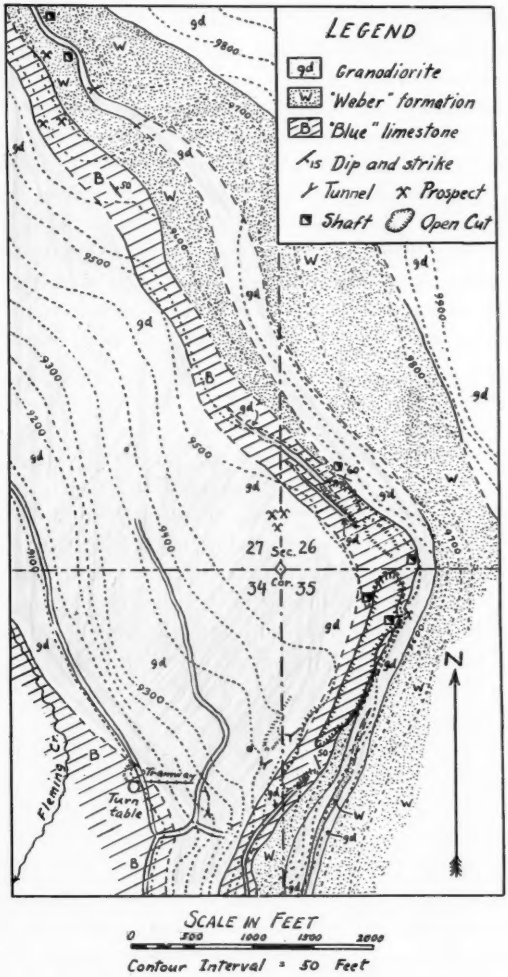

FIG. 8. Detailed topographic and geologic map showing the surface workings of the Calumet mine.

now partly caved and wholly inaccessible; they are described as consisting of inclined chambers in the ore, following the dip downward to the east.

The accessible mine openings consist of two open cuts; the southerly is about 400 feet long and averages 50 feet in width and about 30 feet in depth. About 120 feet north of its northern end is the southern edge of the other open cut; this is about 100 feet long, 30 feet wide and 20 feet deep. An incline begins just west of the south open cut and is said to have led eastward down the dip, in the foot wall of the ore. Two smaller inclined shafts are at the eastern edge of the ore body. Several tunnels with portals down hill from the open cut lead eastward into the hillside toward the ore. The mine was equipped with a tracked, inclined tramway leading from the main shaft and open cut to the level of the road, 400 feet below.

All of the mine workings are located in or near a lens of upper "Blue" limestone, immediately beneath the basal "Weber." The relation of this lens to the overlying and subjacent sills of granodiorite can be inferred from the map. The limestone dips beneath the upper sill at angles varying from 40 to 60°. Two smaller sills lie within the limestone at the northern open cut, and one, possibly to be correlated with one of those just mentioned, extends southward from the southern end of the southern pit. Alteration is so intense, however, that these sills cannot be followed for long distances.

At the mine the "Blue" limestone, where not silicated, is highly bleached. Besides being generally epidotized, it bears occasional nests and numerous bands of magnetite, the latter alternating with diopside in widths of two inches or less. Such banding is parallel to the bedding and apparently represents selective replacement. Where, as in the southern cut, the alteration is most intense the altered granodiorite has numerous tongues, nearly, but not exactly parallel to the bedding, which lie within the limestone mass. Inclusions of limestone up to 10 by 5 by 2 feet in size are found within the higher sill. Along the east wall in the southern part of the south cut, the granodiorite also clearly

transgresses the bedding, and here the epidote occurs in veins and lenses within the granodiorite. In such conditions the mapping of the limestone-sill contacts as shown on the map is necessarily highly generalized. In the north pit a small practically vertical fault is seen, but is apparently later than mineralization.

The distribution of the ore in the mineralized zone is irregular, but the following section, taken across the larger open cut near its northern end, gives some idea of variations in the nature of the mineralization.

Top of Section as Exposed	Approximate thickness, feet
Silicates, especially garnet, and silica, forming a brown layer	2½
Brown, massive beds, averaging 6 inches thick; some beds two inches thick are of magnetite and highly friable	7½
Altered greenish limestone with diopside and fine stringers of magnetite	5
Bed of solid magnetite	1
Barren layer of silicates	½
Bed of solid magnetite	1
Banded magnetite, epidote, and diopside, the silicates predominating	4½
Massive magnetite	2

All the rock in this section is "Blue" limestone. Since the changes in mineralization are parallel to the beds, they are doubtless attributable to variations in composition (predominantly in magnesium content) and perhaps also in shattering.

North and south of the mine along the strike of the limestone lens other small prospects have been opened, but in none of these localities was ore deposition of importance. These prospects clearly outline the areal extent of the workable ore body.

Causes for Localization of the Ore.—It is probable that a combination of factors contributed to bring about this rather remarkable localization of the ore. The regional map (Fig. 3) shows the southwestern edge of the plug-like mass, which, as pointed out previously, was the source of the igneous sills. The ore is developed at a point where the chief sill has an unusually great thickness and where this sill and a lesser sill come close together vertically and are separated by none of the more refractory beds of the "Weber" (which intervene farther north and south)

but only by "Blue" limestone. Indeed, limestone fragments of varying sizes are conspicuous here as inclusions within the sills. This feature, when associated with contact metamorphism recalls similar conditions as reported by Prescott [29] and by Singewald and Miller,[30] as a result of their studies respectively of various Mexican deposits and of the Daiquiri iron ores. At Calumet, in this meeting place of so many sills, with numerous small fragments of replaceable country rock, metamorphic action is most intense and limestone most altered to ore.

It is not easy, however, to explain such close association between this locality of conspicuously complete silication with the more intense ore deposition, especially in view of the clear-cut evidence that silication took place before ore deposition. Van Hise has shown that an alteration from dolomite (the dominant mineral in the original "Blue" limestone) to diopside or tremolite (the chief alteration products observed) should be attended by a volume increase of 2.03 and 9.9 per cent., respectively, if silica is added and is not merely derived from the metamorphosed country rock.[31] The upper "Blue" limestone is not rich enough in silica to yield the necessary amount for either of the two silicates mentioned and seldom bears as much as 1 per cent. silica, as is evident from petrographic studies of specimens collected by the writers, from new analyses of similar beds at Leadville made available to us by courtesy of the Director of the United States Geological Survey, and from analyses already published.[32] Only one case is on record where the silica is high enough to furnish tremolite or diopside without addition of silica from outside sources. The existence of many large openings as the result of

[29] Prescott, Basil: Some Observations on Contact Metamorphic Deposits. ECON. GEOL., vol. 10, pp. 64–66, 1915.

[30] Singewald, J. T., Jr., and Miller, B. L.: The Genesis and Relations of the Daiquiri and Firmeza Iron-Ore Deposits, Cuba. Am. Inst. Min. Eng. Trans., vol. 53, p. 71, 1916.

[31] Van Hise, C. R.: A Treatise on Metamorphism. U. S. Geol. Surv. Mon. 47, p. 241, 1904.

[32] Emmons, S. F., Irving, J. D., and Loughlin, G. F.: Geology and Ore Deposits of the Leadville Mining District, Colorado. U. S. Geol. Surv. Prof. Paper 148, p. 35, 1927.

shrinkage due to silication and the consequent localization of ore by the filling of such openings seem therefore highly unlikely, despite the sporadic and limited occurrence here, as in other districts, of joints and other fissures bearing contact metamorphic silicates such as the idiomorphic epidote crystals mentioned above.

From what has been said on a preceding page, it seems necessary to postulate a series of events involving first, silication with the addition of much silica from the magma, and then the deposition of iron oxide by selective replacement of the silicates thus formed. The question may well be raised as to how relatively insoluble silicates, such as the diopside, were attacked by the iron-depositing solutions. There seems to be good reason for accepting the presence of a cover 2,000 feet thick at the time of ore deposition; much of this consisted of tight shales, impervious to rising gases. If the iron was carried as a component in a gaseous state with chlorine or other halogens as additional components, the solubility of the silicates would be greatly increased, and replacement in which iron ions figured prominently would be possible.[33] To the writers, the observed mineral sequence opposes Butler's brilliant suggestion that the carbon dioxide liberated at contact zones caused the oxidation of iron to yield the iron oxides;[34] for the field and microscopic evidence cited above suggests that iron deposition followed *some time after* the destruction by silication of free limestone close to the contact.[35]

The details of the localization of magnetite and the attendant ore minerals are even less readily understood. In the banded deposits described above and illustrated in Fig. 5, the localization may best be ascribed to slight differences in the original composition or of the products resulting from silication of adjacent beds.

[33] See, for example, in this connection: Fenner, C. N.: Pneumatolytic Processes in the Formation of Minerals and Ores. Am. Inst. Min. Met. Eng., Lindgren vol. (Ore Deposits of the Western States), pp. 88–90, 91–92, 1933.

[34] Butler, B. S.: A Suggested Explanation of the High Ferric Oxide Content of Limestone Contact Zones. ECON. GEOL., vol. 18, pp. 398–404, 1923.

[35] It must be admitted, however, as pointed out by Butler, that ferric iron may have appeared somewhat earlier than the ore in the contact zone in the form of silicates, such as garnet and epidote.

OUTLYING ORE DEPOSITS.

In addition to granodiorite quarrying (a small but steady industry), limestone and marble quarrying for flux, and graphite mining, it is interesting to note that various small metal mines have been operated in the neighboring region. Approximately one and a half miles due south of the Calumet mine is a gold prospect, the Iron King mine (Fig. 3) in a mineralized zone along the westerly of the two faults previously described. The "Blue" limestone (the ore-bearing horizon) is here heavily shattered and silicified, and hematite staining is conspicuous. A few assays are reported to have shown $60 per ton in gold. This apparently represents a "satellitic" or outlying deposit similar to those associated with other contact metamorphic deposits. Smaller deposits of the same sort are known to have been mined in Section 35, S. W. quarter of the S. W. quarter. Perhaps the gold shoots still worked on a small scale at Turret, two miles west of the Calumet mine, are to be regarded similarly.[36]

Likewise the prospects grouped with the Venture mine and opened in 1914, developed some small manganese deposits in the north central part of T. 50 N., R. 9 E., Section 2. These ores apparently represent a mesothermal phase. They show chiefly pyrolusite and limonite, but also small amounts of primary manganosiderite and siderite in veinlets as limestone replacements.

The chief interest attaching to these small outlying ore deposits is that they complete the picture of this as a typical though small-scale contact metamorphic district.

NORTHWESTERN UNIVERSITY,
EVANSTON, ILLINOIS,
August, 1936.

[36] See, however, Lindgren, Waldemar: Notes on Copper Deposits in Chaffee, Fremont, and Jefferson Counties, Colorado. U. S. Geol. Serv. Bull. 340, pp. 157–174, 1908. Lindgren assigned the Sedalia copper mineralization (pp. 161–166) to the pre-Cambrian and suggested (p. 166) that the copper at Turret, about six miles away, is of the same age. Whether the gold veins at Turret are also of that age is uncertain.

A ZONAL GOLD MINERALIZATION IN NOVA SCOTIA.

W. H. NEWHOUSE.

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INTRODUCTION.

NOVA SCOTIA is an excellent region in which to study mineral zoning in gold deposits. The several features favorable for determining zonal relations include a number of intrusive heat centers, one mineralization as is shown by both the mineralogy and structural relations, and a long known and well prospected region with numerous mines and prospects. The study of the gold deposits has shown a pronounced zonal arrangement of minerals with reference to the granite masses.

The deposits range in mineralogical type from hypothermal through many of mesothermal character, to others exhibiting some epithermal mineral features. This is an extreme variation as compared with the zoned gold deposits elsewhere that are described in the literature.

The province thus affords a splendid opportunity for the study of the interrelations of gold vein types and mineral phenomena which have been previously described only as isolated occurrences.

Twenty-eight of the gold districts (Fig. 2) have been visited by the writer. In addition to the extensive collections then made, there was available for study samples of ores and wall rocks of the region which had been obtained over a long period of years by members of the Geology Department of the Massachusetts Institute of Technology.

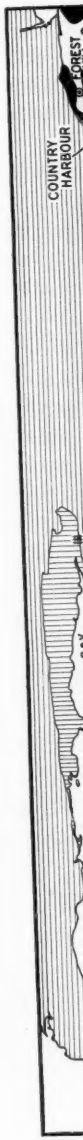
The accompanying map (Fig. 1) does not include some minor deposits in the southwestern part of Nova Scotia, and some of the districts within the map area were not visited and are consequently not considered in the present study.

GENERAL GEOLOGY.[1]

The gold bearing region is some 10 to 40 miles wide and extends along the southeastern coast of Nova Scotia for a distance of over 200 miles. In the northeastern part of the region the pre-Cambrian sedimentary rocks in which the veins occur are bounded on the northwest by sedimentary rocks of Carboniferous age. The southwestern part of the belt is bounded on the north by Devonian granites. The area is one of low relief, elevations seldom attaining much over 700 feet. The higher topographic features are produced by the large granite intrusives.

Sedimentary Rocks.—The sedimentary rocks consist of the pre-Cambrian Gold-bearing series, which includes the Goldenville formation and the partly overlying Halifax formation. Quartzite, in places felspathic, predominates in the Goldenville formation with smaller amounts of slate, grits and conglomerate. Numerous thin beds of slate are interlaminated with the quartzite. The younger Halifax formation consists mainly of slates with some siliceous beds. The exposed thickness of the series has been estimated at 28,000 feet or over, although due to the presence of folds and faults this estimate may be too large. The base of

[1] This part of the paper to "Zonal Mineralization" is summarized largely from Malcolm, W., and Faribault, E. R.: Gold Fields of Nova Scotia. Geol. Surv. Can., Memoir 156, 1929.



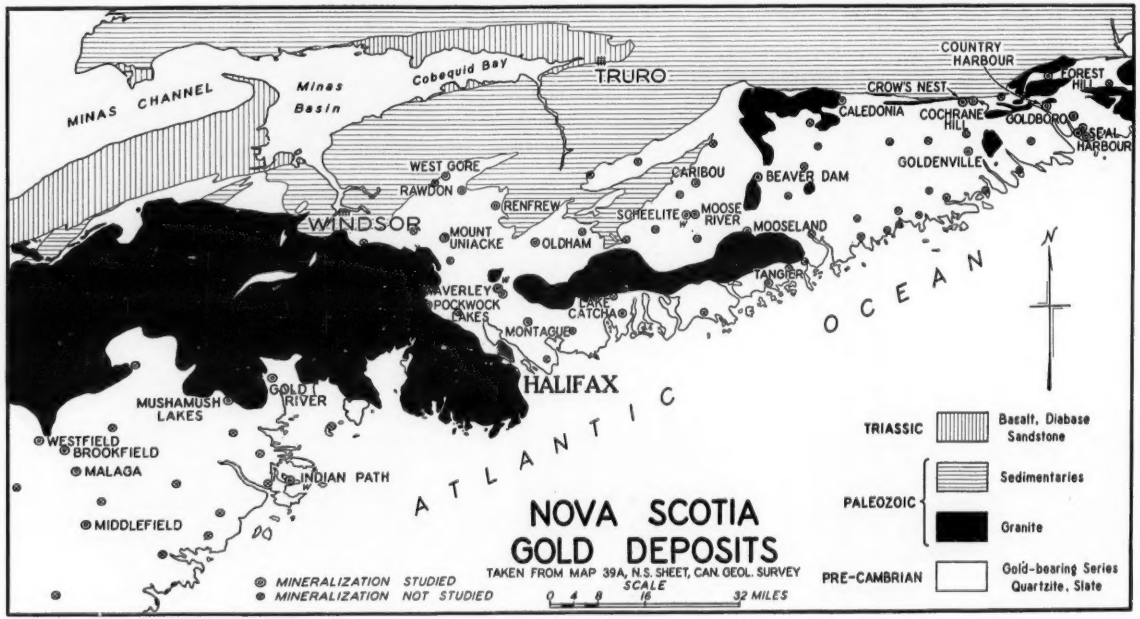

MINAS CHANNEL
Minas Basin
Cobequid Bay
TRURO
COUNTRY HARBOUR
FOREST HILL
CROW'S NEST
CALEDONIA
COCHRANE HILL
GOLDBORO
SEAL HARBOUR
GOLDENVILLE
WEST GORE
RAWDON
CARIBOU
BEAVER DAM
RENFREW
WINDSOR
MOUNT UNIACKE
OLDHAM
SCHEELITE
MOOSE RIVER
MOOSELAND
TANGIER
WAVERLEY
POCKWOCK LAKES
LAKE CATCHA
MONTAGUE
HALIFAX
GOLD RIVER
MUSHAMUSH LAKES
WESTFIELD
BROOKFIELD
MALAGA
INDIAN PATH
MIDDLEFIELD
ATLANTIC OCEAN
N
NOVA SCOTIA
GOLD DEPOSITS
TAKEN FROM MAP 39A, N.S. SHEET, CAN. GEOL. SURVEY
MINERALIZATION STUDIED
MINERALIZATION NOT STUDIED
SCALE
0 4 8 16 32 MILES
TRIASSIC
Basalt, Diabase Sandstone
PALEOZOIC
Sedimentaries
Granite
PRE-CAMBRIAN
Gold-bearing Series Quartzite, Slate

FIG. 1.

the series is not exposed. The Gold-bearing series is in contact with Silurian-Devonian rocks in Kings County. No distinct stratigraphic break between these and the Gold-bearing series has been found. This suggests that extensive folding of the series did not take place before Devonian time.

Lower Carboniferous limestone, sandstone and shale rest unconformably on the Gold-bearing series and the granite.

Placer gold has been found in the basal conglomerates of the Lower Carboniferous sediments.

Igneous Rocks.—A few small basic intrusives are found particularly in the southwestern part of the region. The chief intrusive rock is granite, which is widely distributed in various sized masses; some, five to ten miles across, are found in the eastern part of the region, and a large one occupies some hundreds of square miles in the western part. The texture and composition of the granite varies greatly.

In Guysborough and Halifax counties [2] the granite of the large masses is composed of white or pink feldspar, quartz, and white silvery mica; their centers are commonly porphyritic. Dikes of granite and pegmatite are common in the older sedimentary rocks near them, and also occur at some distance from them.

Detailed work [3] in the New Ross Area has shown that two types of granite are present: a biotite granite with phenocrysts of microcline and a groundmass of plagioclase, orthoclase, quartz, and biotite, and a later muscovite granite containing more quartz and with phenocrysts of orthoclase in a groundmass of orthoclase, plagioclase, quartz, biotite and muscovite. Aplite is associated with the earlier granite and both aplite and pegmatite with the later one.

"Judging from the mineral composition and the nature of the contact of the two granites, it is possible that they are closely related in origin and age." [4]

The granite is later than early Devonian sedimentary rocks and is earlier than the Horton series, and is thus of Devonian age.

[2] Faribault, E. R.: Can. Geol. Surv, Ann. Rept. vol. 2, p. 132, 1886.
[3] Wright, W. J.: Can. Geol. Surv., Summ. Rept., pp. 386–387, 1912.
[4] Wright, W. J.: *Op. cit.*

Schists and gneissic rocks are widely distributed in limited amounts which form more or less continuous zones surrounding the granite intrusions. Some areas are also found several miles distant from the granite.

Structure.—The dominating structural feature is a series of large anticlines and synclines in the Gold-bearing series. The folds trend easterly in the eastern part of the region and northeasterly in the western part, and are more tightly compressed in the former. Most of the folds are unsymmetrical with the axial planes generally dipping north. Domes are present along the anticlines and it is with these structures that many of the gold deposits are found.

Local faults are found in the gold districts. They appear to be related to the doming of the rocks and commonly radiate from the center of a dome.

Faults of considerable length and displacement are also known, particularly in the eastern part of the region. These generally strike northwest and extend across several folds, displacing the rocks horizontally, in some instances one-half to one and one-half miles.

RELATIONS OF VEINS TO ENCLOSING ROCK.

Some gold-bearing quartz in granite has been reported, but little definite information is available on such occurrences.[5]

The veins are largely confined to the Goldenville formation where they occur chiefly in thin beds of slate within this great thickness of quartzites. Few paying veins have been found in the Halifax formation. The bulk of the veins parallel the strata, most of them are within slate beds a few feet thick. They are commonly near or at the base of the slate, adjacent to a foot-wall of quartzite. In addition to the interbedded type of vein, there are a few that cut across the bedding and are termed cross veins, such as those at Brookfield and other districts.

Branch veins may extend into the hanging-wall and foot-wall; these are termed angulars.

[5] Malcolm, W., and Faribault, E. R.: *Op. cit.*, p. 41. Messervey, J. P.: Stormont Gold District, Nova Scotia. Dept. of Public Works and Mines, p. 36. Refers to gold in granite near Forest Hill.

The gold-bearing veins are mainly in the domes and here the interbedded veins are intimately related to the details of structure and folding.

Generally the veins appear on a dome where the strata are most curved by folding. Hence on a sharply folded anticline they are found on the crest and form saddles, but on the broader, flat topped folds, they occur on the sides where the dip is most changeable.

ORE SHOOTS.

The ore shoots vary from 20 to 60 feet and more in breadth. Several shoots have had a length of 1,200 to 2,000 feet down the dip. The maximum vertical depths of these was about 1000 feet, but many have been worked only to depths of 300 to 400 feet.

The shoots in the interbedded veins are generally controlled or related to a subordinate crumble or " roll " in the dome. A dome may contain a number of interbedded veins at different stratigraphic horizons, and where a subordinate flexure or apex of the main fold contains an ore shoot in one of these veins, shoots may also be present where the flexure intercepts the others. Faribault has given considerable attention to this relationship which he has termed the Pay Zone theory.

Other features which are known to be related to local enrichment of gold values are certain angulars, and certain slate beds, which are intersected by cross veins.

ZONAL MINERALIZATION.

The mineralization differs considerably in the various districts, but with very few exceptions the principal vein constituent is quartz. Arsenopyrite is present in all the districts studied by the writer. Pyrite is also always present, usually in lesser quantity than arsenopyrite. Certain other minerals in the veins, the wall rock alteration, and the quantity of gold varies with distance from the granite stocks or batholiths.

Zone I. Inner High Temperature Zone.—High temperature minerals are commonly present in the gold quartz veins near the granite intrusives (Fig. 2). Veins within one and one-quarter

DISTRICT	DISTANCE IN MILES FROM GRANITE INTRUSIVE	ANDALUSITE	GARNET	OLIGOCLASE	HORNBLENDE	BIOTITE	MUSCOVITE	TOURMALINE	EPIDOTE	ILMENITE	RUTILE	MOLYBDENITE	PYRRHOTITE MASSIVE	ARSENOPYRITE	PYRITE	CHALCOPYRITE	SPHALERITE	GALENA	STIBNITE	PYRRHOTITE CRYSTALS	QUARTZ	ALBITE	ANKERITE	CALCITE	SERICITE	CHLORITE	VALENTINITE	WOLFRAMITE	SCHEELITE	APATITE	NATIVE ANTIMONY	NATIVE GOLD
COUNTRY HARBOUR	¼		X	X		X	X	X					X	X	X	X					X			X		X		X				X
POCKWOCK LAKES	¼			X		X	X		X		X		X	X	X						X	X		X	X	X						X
CALEDONIA	½		X			X	X	X					X	X	X						X	X			X	X						X
MUSHAMUSH LAKES	½						X	X					X	X	X	X					X	X	X		X	X						X
FOREST HILL	½		X	X		X		X	X				X	X	X						X				X	X		X	X	X		X
MOOSELAND	¾		X	X	X	X	X	X	X		X		X	X	X						X			X	X	X		X	X	X		X
COCHRANE HILL	¾	X	X	X	X	X	X	X	X	X	X		X	X	X			X			X	X		X	X	X		X	X	X		X
CROWS NEST	¾	X	X	X	X	X	X	X	X	X			X	X	X						X					X		X	X	X		X
WESTFIELD	1						X	X					X	X	X						X					X		X	X			X
BEAVER DAM	1¼		X	X	X	X	X	X	X	X			X	X	X			X			X	X	X			X		X		X		X
GOLD RIVER	1½												X	X	X			X			X		X	X	X	X						X
MOUNT UNIACKE	2½						X	X					X	X	X						X		X	X		X		X				X
GOLDENVILLE	2½						X	X					X	X	X		X	X			X		X	X		X		X	X			X
WAVERLEY	2½												X	X	X		X	X			X		X	X		X		X	X			X
TANGIER	3							X					X	X	X						X	X		X		X						X
MONTAGUE	3½					X							X	X	X		X	X			X		X	X		X		X	X	X		X
BROOKFIELD	3½													X	X						X		X	X		X						X
LAKE CATCHA	3¾												X	X	X						X		X	X	X	X						X
GOLDBORO	4			X	X	X	X	X	X				X	X	X		X	X			X	X		X		X		X	X			X
OLDHAM	5½												X	X	X		X	X			X		X	X		X						X
LOWER SEAL HARBOUR	6						X	X					X	X	X						X		X	X		X						X
MOOSE RIVER	6							X					X	X	X		X	X			X		X	X		X		X	X			X
MALAGA	7½					X							X	X	X						X		X	X		X		X	X	X		X
CARIBOU	8						X	X					X	X	X						X		X	X	X	X		X	X	X		X
RAWDON	12						X							X	X						X		X	X		X						X
WEST GORE	12½													X	X	X	X	X	X	X	X	X	X	X	X	X	X				X	X
RENFREW	13													X	X	X					X		X	X		X						X
MIDDLEFIELD	20						X						X	X	X						X		X	X		X						X

FIG. 2. Mineral chart of Nova Scotia gold districts. Largely made from the writer's observations. Minerals such as galena, sphalerite, etc., generally present only in small amounts have probably been overlooked in some districts.

miles of the stock-like or batholithic intrusions,[6] as at Cochrane Hill, Crows Nest, Forest Hills, Country Harbour, Beaver Dam, Mooseland, Little Liscomb Lake near Caledonia, Pockwock Lakes and Westfield, contain such minerals as biotite, muscovite, oligoclase feldspar, hornblende, garnet, tourmaline, epidote, ilmenite and pyrrhotite. These minerals are widely present in varying amounts in or associated with the veins, and of less common occurrence are andalusite and molybdenite. (Fig. 2.)

The quartz where not crushed is coarse grained. These deposits have the mineral characteristics of Lindgren's hypothermal group. Some of them are clearly among the highest temperature gold deposits yet described. Close similarity is seen, for example, between the Cochrane Hill, Crows Nest, Mooseland and Beaver Dam deposits with those of the Passagem Lode in Brazil [7] and in the James River Basin, Virginia.[8] In these, oligoclase or andesine feldspar, biotite and ilmenite are present with other high temperature minerals. The grey green oligoclase or andesine, in crystals 1 to 2 inches across, is usually found on or near the walls of the vein. It is clearly one of the earliest minerals. Such veins carrying oligoclase have been called pegmatite.[9]

Biotite is pretty well confined to the inner or first zone. It forms flakes several millimeters across, as compared with the muscovite flakes which in the highest temperature deposits, may exceed one centimeter in diameter. The biotite flakes that commonly form a vein selvage or lie within the quartz are mostly several times larger than those in the adjacent wall rock. This coarse biotite is commonly accompanied by sulphides. Pink garnet in small crystals is more abundant in the wall rock than in

[6] Granite dikes found at Cochrane Hill, Crows Nest, and other places are not considered.

[7] Hussak, E.: Der goldführende, kiesige Quarzlagergang von Passagem in Minas Geraes, Brazilien. Zeit. für Prakt. Geol., pp. 345–357, 1898. Derby, O. A.: On the Mineralization of the Gold-bearing Lode of Passagem, Minas Geraes, Brazil. Am. Jour. Sci., 4th ser., vol. 32, pp. 185–190, 1911.

[8] Taber, Stephen: Geology of the Gold Belt in the James River Basin, Va. Va. Geol. Surv. Bull. 7, 1913. Feldspar determinations by E. S. Larsen.

[9] Hussak, E.: *Op. cit.* Ross, C. S.: Origin of the Copper Deposits of the Ducktown Type in the Southern Appalachian Region. U. S. Geol. Surv. Prof. Paper 179, pp. 24–25, 51, 62–63, 1935.

the quartz, but thin sections frequently show increase of the garnets in the wall rock immediately adjacent to quartz veins. Tourmaline is present as small black prisms, commonly abundant in both the quartz vein and adjacent wall rock.

Andalusite is present in the form of prisms one to two centimeters long in the quartz veins at Cochrane Hill and Crows Nest.

Fine grained molybdenite forms thin veins in the quartz at Big South Lead Mooseland, and was also seen at Forest Hill.

Ilmenite is present in the slate wall rocks at Cochrane Hill, Crows Nest, and Beaver Dam, and ilmeno-rutile is reported at Mooseland.[10]

The evidence indicates that the titanium has not been introduced by solutions, but rather that it was present in the shales when deposited as sediments. However, it has been rearranged to form larger and locally numerous crystals, in small wall rock inclusions in the veins, and in narrow portions of the wall rocks immediately next to the high temperature veins. It forms lens shaped crystals, about 1 mm. long. It is clear that in the high temperature veins the ilmenite was in approximate equilibrium with the vein solutions.

In the mesothermal type deposits leucoxene is present in the slate wall rocks as much smaller masses of irregular outline. They show no signs of having been moved or locally concentrated by vein solutions. They are at least partly derived from ilmenite and titaniferous magnetite of detrital or metamorphic origin.

The veins adjacent to the largest intrusion of granite, at Westfield, Pockwock Lakes and Clearland, show lower temperature mineralogy than is found in the veins adjacent to the smaller granite intrusions. A smaller number of species of high temperature minerals is present, and the species represented are not so abundant in quantity.

Zone II. Intermediate Temperature Zone.—A second zone of lower temperature mineralogy is found at a distance of one and one-half miles and more from the granite intrusions (Goldboro excepted). Some variation is found in deposits transitional be-

[10] Malcolm and Faribault: *Op. cit.*, p. 43.

tween Zones I and II, but the bulk of the deposits show typical mesothermal characters. Such are the veins, for example, at Brookfield, Middlefield, Montague, Waverly, Uniacke, Rawdon, Renfrew, Oldham, Lake Catcha, Caribou, Moose River, Tangier and Sherbrooke.

The chief minerals are quartz, carbonate, chlorite, arsenopyrite and pyrite. (Fig. 2.)

The quartz is coarse grained, but in general less so than that in the veins of Zone I; the difference is not marked. It is milk-white and in places drusy. The rough banding is generally due to strips of slate included in the quartz, sulphides, carbonate and to shearing of the quartz.

Carbonate is in general one of the most abundant constituents in the veins of Zone II. It and arsenopyrite rank after quartz in abundance. This contrasts with Zone I where carbonate is rare. Two generations of carbonate of different composition are present. The first generation consists of ankerite and is one of the first minerals deposited with the possible exception of arsenopyrite in the wall rock. The ankerite commonly forms selvages to the small veins, and presents enhedral crystal outlines to the later quartz. The ankerite crystals attain 1 to 2 cm. across. Similar early carbonate selvages to vein walls and wall rock inclusions are found elsewhere with gold veins [11] and Charlewood [12] finds pre-ore ankerite with many gold bearing quartz veins of the Canadian shield. Quartz in places veins the carbonate and replaces it but apparently in no great amount. In many of the veins, particularly those over a few inches in thickness, the ankerite selvage has been sheared along planes parallel to the vein wall and dragged in the form of thin plates or lenses, into the quartz vein where they form alternating slices of carbonate with the quartz, all roughly parallel to the wall. The carbonate in

[11] Spencer, A. C.: The Juneau Gold Belt, Alaska. U. S. Geol. Surv. Bull. 287, p. 113, 1906. Junner, N. R.: Gold Occurrences of Victoria, Australia. Econ. Geol., vol. 16, p. 98, 1921. Knopf, A.: The Mother Lode System of California. U. S. Geol. Surv. Prof. Paper 157, p. 35, 1929.

[12] Charlewood, G. H.: Nature and Occurrence of Carbonates in Veins. Econ. Geol., vol. 30, p. 517, 1935.

these slices often commonly displays long twin bands or laminae approximately parallel to the shear plane.

The later or second generation of carbonate is calcite containing small amounts of iron and manganese as shown by optical and chemical examination. It commonly surrounds quartz grains where pronounced mortar structure is present in the quartz, and forms small vein networks that traverse the crushed vein quartz crystals. These networks of carbonate may be connected with vugs in the quartz, which contain calcite.

A very small amount of muscovite or coarse sericite is widely present within the quartz veins.

Zone III. Outer Zone.—A lower temperature mineralization than that characteristic of Zone II is found at West Gore. Although not the farthest from the granite as measured by surface exposures, it is the farthest northeast of the large granite intrusive.

The chief minerals are quartz and stibnite, with lesser amounts of bladed pyrrhotite, native antimony, arsenopyrite, pyrite, sphalerite, chalcopyrite, low iron ankerite, albite and chlorite, valentinite and native gold. Kermesite is reported.

Banding by deposition is absent but the minerals are fine grained, mostly averaging less than one millimeter in diameter and rarely above several millimeters. The quartz is finer grained than that in the typical mesothermal type veins and some of it contains small vugs.

Quartz is the earliest mineral deposited, with the possible exception of the arsenopyrite and pyrite, which are largely confined to the wall rock.

The original quartz in the veins contains abundant, small liquid and gas inclusions, which give it a cloudy grey appearance under the microscope in ordinary light. Minerals have been introduced along fractures in it. The crushing that produced the fractures, which are more or less plane-like in character, also has produced mortar structure around the margins of individual quartz grains. Cementation or healing of the fractured quartz has been by new clear quartz with the same crystallographic orientation as the

original grains. Many of these veins of new quartz with accompanying stibnite can be seen better on microscopic examination with ordinary light than with crossed nicols. Pyrrhotite follows the quartz and is present as radiating aggregates or rosettes of small strongly magnetic plates that are commonly less than 1 mm. in length. The crystals have replaced the quartz vigorously and to a less extent the wall rock. This unusual form of pyrrhotite is believed to be one of the low temperature forms such as has been described as forming rosette-like aggregates, crusts, and small crystals from several places.[13]

An occurrence of small pyrrhotite crystals in calcareous sandstone of Clinton age in central New York is also strongly suggestive of low temperature origin.[14] Associated minerals are dolomite, calcite, quartz, celestite and strontianite. The pyrrhotite is later than the dolomite, quartz and calcite.

Well defined pyrrhotite crystals, although rare in American ores, are found in a number of European deposits.[15]

Some of the associations described are suggestive of a low temperature origin, but that all such crystals are low temperature[16] pyrrhotite is doubtful.

The ankerite in the West Gore mineralization is in veins in fractured quartz. Stibnite replaces quartz, carbonate, pyrrhotite,

[13] Keilhack, K.: Ueber praglaziale Südwasserbildungen im Diluvium Norddeutschlands. Jahrb. d. Preuss. Geol. Landesanst., pp. 133–172, 1882. Harbort, E.: Ueber Zonar in Steinsalz und Kainite eingewachsene Magnetkieskristalle aus dem Kalisalzbergwerk Aller-Nordstern. Kali 9, pp. 250–253, 1915. Berg, G.: Die schottischen Oelschiefer. Zeit. für prakt. Geol., pp. 98–103, 1914. Frebold, G.: Ueber eine bemerkenswerte Paragenese von Brauneisen, Magnetkies und Pyrit mit Bitumen in Schichten der Unteren Kreide von Ahlem bei Hannover. Neues Jahrb., Beil. Bd. 64A, pp. 691–700, 1931.

[14] Smyth, C. H.: A New Locality of Pyrrhotite Crystals and Their Pseudomorphs. Am. Jour. Sci. 4th ser., vol. 32, pp. 156–160, 1911.

[15] Hintze: Handbuch der Mineralogie. Bd. I, Abt. 1, pp. 635–637. Buschendorf, F.: Neues Jahrb., Beil. Bd. 62A, pp. 24–26, 1931.

[16] Pure FeS inverts at 140°, and with increasing sulphur content the transformation temperature is lowered. Two low temperature forms are known, one low in excess sulphur and not appreciably magnetic, the other high in excess sulphur and strongly magnetic. Ann. Rept., Director Geophy. Lab. for 1930–31, p. 85; also, Allen, Crenshaw, Johnston & Larsen: Am. Jour. Sci., 4th ser., vol. 33, pp. 193–236, 1912, who formed small pyrrhotite crystals at 80° C.

sphalerite, and selectively replaces certain minerals in the sandy portions of the slate, leaving residual grains of quartz.

Native antimony replaces the earlier stibnite, carbonate and sphalerite, and has strongly attacked the pyrrhotite.

Small veins of stibnite and associated valentinite appear in the native antimony. These veinlets are probably supergene in origin. The stibnite is finer grained than the earlier generation of that mineral.

Van der Veen has suggested a supergene origin for veinlets of stibnite in native antimony.[17]

No exact counterpart to the West Gore deposits is known by the writer. Some features are similar to the ores of the National Mine, National, Nevada,[18] and to those of the Globe & Phoenix Mine in So. Rhodesia,[19] and to some veins in Alaska.[20]

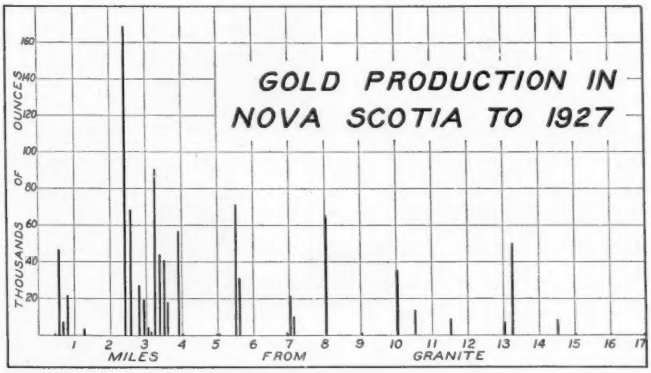


FIG. 3.

Zonal Relations of Gold to the Granite.—Any conclusions on the distribution of vein gold relative to the intrusive granite

17 Van der Veen, R. W.: Mineragraphy and Ore Deposition, p. 69, 1925.

18 Lindgren, W.: Geology and Mineral Deposits of the National Mining District, Nevada. U. S. Geol. Surv. Bull. 601, pp. 30–45, 1915.

19 Keep, F. E.: Report of Director. Geol. Surv., So. Rhodesia, 1927.

20 Brooks, A. H.: Antimony Deposits of Alaska. U. S. Geol. Surv. Bull. 649, 1916.

masses must be based on the assumption that the gold so far found and recovered is representative of the total gold that was initially deposited in the veins at this particular horizon in the earth's crust. In view of the long history—over 75 years—of mining, extensive prospecting in a well populated region, and also because of the large number of districts and mines worked, it is believed that in unusual degree for a mining region, this assumption is approximately true.

As may be seen in Fig. 3, much of the gold comes from veins from 2½ to 4 miles from surface exposures of intrusive granite.[21] Much of the remaining production has come from veins still farther removed. Figure 4 brings out this relationship even

FIG. 4. Relative amounts of gold and areas within certain distances from the granite.

more forcibly. Although 30 per cent. of the total pre-Cambrian area is within 2½ miles of intrusive granites, only 8 per cent. of

[21] Data obtained from Nova Scotia sheet, Can. Geol. Surv., also the separate 1 mile to 1 inch geology maps, and from the production figures in Mem. 156, Can. Geol. Surv., p. 240, 1929, supplemented by additional production figures kindly supplied by the Nova Scotia Department of Public Works and Mines.

the total gold production has come from this area. Fifty-seven per cent. of the total gold produced came from the 15 per cent. of total area lying between 2½ and 4 miles from the granite. The remaining 35 per cent. of gold produced came from the 55 per cent. of total area of Gold-bearing series within the map area (Fig. 1) which is over 4 miles from the intrusives.

It is clear that in this region mesothermal conditions favored gold precipitation.

Zonal Variation of Wall Rock Alteration.—The type of wall rock alteration varies according to the type of deposit. At the Cochrane Hill Mine the quartzites and slates have been intruded by numerous granite dikes and have been strongly metamorphosed, containing staurolite, andalusite, garnet and mica, according to Faribault.[22] Similar metamorphic rocks are found in the vicinity of the Crows Nest Mine, and less extensively metamorphosed ones are present in the Mooseland, Beaver Dam, Forest Hill, Country Harbour and other districts visited by the writer.

Thin sections of the wall rocks adjacent to these higher temperature veins, and at some distance away from the veins, show the bulk of the minerals to be the same species in each case. Quartz, plagioclase, biotite and muscovite are the predominant minerals. Biotite and oligoclase show local increases in amounts near the veins. Narrow vein selvages are in places composed almost entirely of these minerals, commonly as coarser grained aggregates than in the wall rock at some distance from the veins.

The important changes brought about by the vein forming solutions are chiefly changes in quantity and often the size of the several mineral species present in the wall rocks.

The metamorphic minerals, biotite and oligoclase, were stable, or were in approximate equilibrium so far as composition of these solid phases were concerned with the incoming vein solutions, which were capable of forming these same minerals. This is particularly true at Cochrane Hill and Crows Nest.

[22] Malcolm, W., and Faribault, E. R.: Can. Geol. Surv., Mem. 156, p. 73, 1929.

Biotite-oligoclase stability was evidently maintained throughout most of the period of vein formation at these two places and only minor chlorite and sericite were formed, with a few small albite veins in the oligoclase, during a late stage of the mineralization.

The mesothermal type veins (16 districts) which include all the districts 1½ miles and farther (except West Gore and Goldboro, especially the Richardson Mine), from the intrusive stock or batholith contacts, display a different type of wall rock alteration.

Ankeritic carbonate has been introduced into both the quartzites and slates, adjacent to the veins, and in the wall rock inclusions. Locally, this carbonate rises to 40 to 50 per cent. of the rock, but commonly it is much less. Weathered surfaces of these rocks display under a hand lens a speckled appearance due to partial oxidation of the iron-bearing carbonate. Under the microscope the carbonate is fairly coarse grained and generally has irregular outlines and commonly encloses corroded quartz grains.

The carbonate in the slates at West Gore is much finer grained than that in the typical mesothermal type deposits.

Sericite and albite are present in most of the wall rocks of the deposits in Zone II that were examined. It is not clear how much of either of these minerals was introduced or formed by mineralization and they are not included in the table of minerals.

Chlorite and quartz "tails" are present with arsenopyrite in the slates.

The dominant wall rock alteration product is ankeritic carbonate. This type of wall rock alteration is common with gold quartz veins for carbonate is a widespread and abundant alteration product in the Canadian pre-Cambrian gold deposits,[23] and it is also the chief alteration product in the Mother Lode wall rocks,[24] and elsewhere.

[23] Beaton, N. S.: Wall Rock Alteration Accompanying Canadian pre-Cambrian Gold Mineralizations. Ph.D. Thesis, M. I. T., 1935.

[24] Knopf, A.: *Op. cit.*, p. 44.

COMPARISON WITH OTHER DISTRICTS SHOWING A ZONED GOLD MINERALIZATION.

Mineral zoning in gold deposits has been described in detail by Hewett and briefly by Rene V. Aubel. The gold lodes of the Sumpter Quadrangle, Oregon, display according to Hewett,[25] a central zone near a quartz diorite batholith, which is relatively high in coarse grained sulphides—pyrite, and arsenopyrite, with less sphalerite, chalcopyrite and galena. The successive outer zones contain the sulphide minerals in decreasing quantities, and the grain or crystal size decreases. The gold in the inner zone is either combined or extremely fine grained while progressively outward the free gold (easily amalgamated) increases steadily.

At Kibukira, Belgian Congo, Aubel[26] found a central zone containing gold-tourmaline-arsenopyrite and a little bismuth. Outside of this is a median zone of gold-pyrite with occasional arsenopyrite and tourmaline. An outer feebly auriferous zone is present.

In the Victoria, Australia gold quartz veins,[27] "there is commonly a zonal change in the mineralogical character of the reefs dependent on their distance from granitic intrusions . . . where the reefs occur within and adjoining such rocks, high temperature minerals such as molybdenite, pyrrhotite, arsenopyrite, garnet, and biotite are present, and in reefs farther removed these minerals are absent or present in small quantities and galena, sphalerite, stibnite and pyrite are more prominent."

Some interesting differences between the Sumpter Quadrangle, Kibukira, and Nova Scotia zonal relations should be mentioned. The Sumpter Quadrangle lodes do not display so great a zonal range as do the latter two examples. The variation is in relative quantity of the same mineral species, and in crystal size. As

[25] Hewett, D. F.: Zonal relations of lodes in the Sumpter Quadrangle. Am. Inst. Min. Met. Eng. Trans., vol. 96, pp. 305–346, 1931.

[26] Aubel, R. V.: Annales de la Soc. Geol. de Belg., pp. 10–11, 1934.

[27] Junner, N. R.: The Geology of the Gold Occurrences of Victoria, Australia. ECON. GEOL., vol. 16, p. 109, 1921.

compared to this the latter two places display variation in both the mineral species and elements present. The brief description of Junner suggests a fairly close similarity between the Victoria and Nova Scotia zonal range.

MINERAL SUCCESSION.

In Zone I oligoclase precedes the quartz, and in Zone II ankeritic carbonate precedes this most abundant vein constituent. Arsenopyrite, which in general is more abundant than pyrite, is generally earlier where age relations are displayed. No evidence of pyrite increase relative to arsenopyrite away from the central zone was found. Both sulphides are commonly later than the quartz, although it is not certain that such is always the age relation. Pyrrhotite in massive form is relatively abundant in the Zone I deposits, with associated silicates, and is found in smaller amounts in some of the Zone II deposits where arsenopyrite and pyrite are much more abundant. It is later than the pyrite and arsenopyrite found with it, and so forms an interesting example of a mineral that is the reverse of the common rule in zoned deposits of "later mineral is in outer zone." Pyrrhotite—the massive form—appears mostly to have the zonal relations to pyrite described in these gold deposits. The sulphides, pyrrhotite and arsenopyrite, are commonly in close association with biotite, in minute, local recrystallized areas in the wall rocks of Zone I. This suggests that they were formed at about the same time, but some of these sulphides and pyrite are clearly later than the biotite within the veins. Tourmaline is present along fractures in the quartz in Zone I, but similar fractures contain chlorite in Zone II. In Zone II low-iron calcite is often found replacing the quartz along fractures.

Chalcopyrite, sphalerite and galena, are later than arsenopyrite and pyrite.

Native gold in all of the zones is commonly along fractures or between grains of the other minerals. It and other late minerals are common in the zones of crushed quartz.

In this region,[28] as in some others,[29] gold is associated with the relatively late mineral galena to sufficient extent so that the lead sulphide is regarded as a good indication of high gold values in a vein.

LOW TEMPERATURE (α) AND HIGH TEMPERATURE (β) QUARTZ.

Quartz from Cochrane Hill and from typical mesothermal type veins, when polished and etched by hydrofluoric acid, show differences in twinning. This difference is thought due to the presence of β, the high temperature form of quartz, in the Cochrane Hill veins, and only α, the low temperature form, in the mesothermal type.

The work on which this is based was suggested by two recent papers by Meen,[30] in which a new examination technique was applied, and the β or high temperature form of quartz was found in some of the northwestern Ontario gold quartz veins. Only low temperature quartz was found in the Kirkland Lake and Porcupine districts in Ontario. Meen in general substantiated the earlier work of Wright and Larsen,[31] except that he found β quartz in some veins, whereas they found "that vein and geode quartzes and certain large pegmatite quartz masses and pegmatite veins were formed below 575°, and graphic and granite pegmatites and granites and porphyry quartzes were in all probability formed above 575°."

[28] Wilson, M. E.: Mineral Deposits in Nova Scotia, etc. Can. Geol. Surv., Summ. Rept., p. 91C, 1926.

[29] Knopf, A.: The Mother Lode System of California. U. S. Geol. Surv. Prof. Paper 157, p. 37, 1929. Lindgren, W.: The Gold Quartz Veins of Nevada City and Grass Valley, Calif. U. S. Geol. Surv., 17th Ann. Rept., Pt. 2, p. 118, 1895–96. Ferguson, H. G., and Gannett, R. W.: Gold Quartz Veins of the Allegheny District, California. U. S. Geol. Surv. Prof. Paper 172, pp. 50, 60, 1932. Ferguson, J. C.: The Geology of the Country Around Filabusi Insiza District, Southern Rhodesia. Geol. Surv. Bull. 27, p. 82, 1934. Maclaren, J. M.: Gold, Its Geological Occurrence and Geographical Distribution, p. 61, London, 1908.

[30] Meen, V. B.: The Etching of Alpha and Beta Quartz. Univ. of Toronto Studies, Geol. Ser. no. 36, p. 37–43, 1934. Meen, V. B.: The Temperature of Formation of Quartz and Some Associated Minerals. Univ. of Toronto Studies, Geol. Ser., no. 38, pp. 61–68, 1935.

[31] Wright, F. E., and Larsen, E. S.: Quartz as a Geologic Temperature. Am. Jour. Sci., 4th ser. vol. 27, pp. 420–447, 1909.

In the present work briquetted fragments of quartz were prepared according to the method of Meen, but much more satisfactory results were obtained on the writer's material by merely etching ordinary polished sections of quartz. In etching the section it was coated with paraffine except for the polished surface. After experimenting with various types of microscopes, the writer used binoculars and a reflecting metallographic microscope for most examinations. Over 70 sections in all were examined.

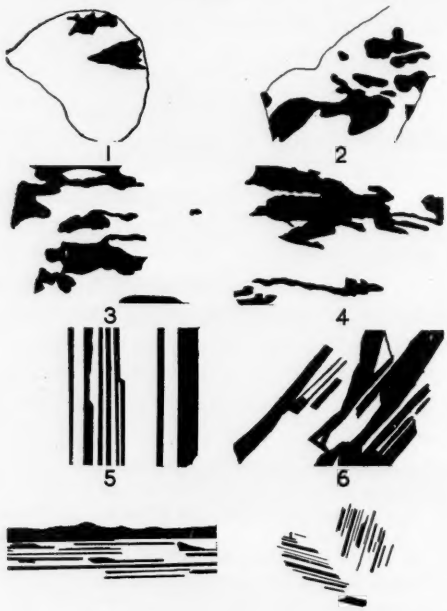


FIG. 5. Twinning in quartz. 1. Quartz grain in granite, Rockport, Mass. × 50. 2. Quartz grain in quartz porphyry, Muldenthal, Saxony. × 50. 3. Quartz from vein, Cochrane Hill, N. S. × 50. 4. Quartz from vein, Cochrane Hill, N. S. × 50. 5. Basal section quartz crystal, Hot Springs, Ark. × 50. 6. Quartz from vein, Moose River, N. S. × 50. 7. Quartz from vein, Moose River, N. S. × 50. 8. Quartz from vein, Hollinger Mine, Ont. × 50.

Sections were made of five different granites, six quartz porphyries, and graphic granite from two different pegmatites. These show a type of twinning similar to Nos. 1, 2 (Fig. 5) and are considered to be β quartz. No twinning like that shown by Nos. 5, 6, 7, 8 (Fig. 5) was seen. For comparison other sections were made of quartz, which, from its geological occurrence, was considered to be the low temperature variety. These included specimens from Hot Springs, Ark., Herkimer Co., N. Y., amethyst from Bidill, Colo., and Germany, and massive vein quartz from some mesothermal type veins, including the North Star Mine, California and several in Nova Scotia. These display the type of twinning shown by Nos. 5, 6, 7, 8.

Parallel straight line edged twinning is common in the α and apparently lacking in the β quartz examined by the writer.

A number of sections were made and examined of the quartz at Cochrane Hill. Based on the criteria mentioned, much of the quartz at this place is apparently the β or high temperature variety.

The mineralization at this place appears to have in part taken place above 575° C. Since granite pegmatites crystallize in part above that temperature and in part below, the Cochrane Hill veins can hardly be regarded as having formed from cooler phases of the granite pegmatite solutions.

SIGNIFICANCE OF FELDSPARS ASSOCIATED WITH ORE DEPOSITS.

Mineralization, at a number of places in the world, containing oligoclase or other feldspars with a higher ratio of calcium than albite, commonly,[32] although not always,[33] have a high tempera-

[32] Zone I, this paper. Composition between ab 10 an 90—ab 30—an 70. Taber: *Op cit.;* Ross: *Op. cit.;* Hussak: *Op. cit.* Beyschlag, Krusch, Vogt: Die Lagerstatten der nutzbaren Mineralien und Gesteine. Vol. 1, pp. 333–336, 1910 (Bodenmais). Eskola, P.: On the Petrology of the Orijarvi Region in Southwestern Finland. Comm. Geol. Finlande, Bull. no. 40, pp. 234–240, 272–273, 1914. Geijer, P.: Riddarhyttans Malmfalt. Bull. 1, Dept. Comm., Stockholm, pp. 56–57, 1923.

[33] Ferguson, H. G.: Gold Quartz Veins of the Allegheny District, California. U. S. Geol. Surv. Prof. Paper 172, p. 44, 1932. Hirschi, H.: Lagerstatten von krystallisiertem Gold in einem Kalkmassive zu Totok, Nordost-Celebes. Zeit. für prakt. Geol., pp. 213–214, 1911.

ture assemblage of minerals. They have consequently been termed pegmatite by several writers. In addition to the andesine and oligoclase feldspars present in the highest temperature range of hypothermal veins, albite is common [34] in the lower temperature range of the hypothermal group, and in the mesothermal group. Orthoclase (adularia) is a common mineral in the epithermal group of gold veins.[35] Logic demands that if one of these gold-quartz-feldspar mineralizations is called pegmatite, they all should be so designated.

It may be recalled that feldspars are also formed in contact metamorphic deposits.[36] Few geologists would consider these of pegmatitic origin.

It may also be pointed out that anorthite well above oligoclase in the Ca-Na ratio is present in contact metamorphic deposits,[37] and high grade (temperature) metamorphic rocks.[38]

Low temperature feldspars (adularia) found in contact metamorphic deposits, that have been carefully examined, are found to be late minerals.[39]

In summary, the writer believes that there is much data supporting the view that although original composition of solutions is important in determining the kind of feldspars that may be

[34] Lindgren, W.: Mineral Deposits, p. 530. Knopf, A.: The Mother Lode System of Calif. U. S. Geol. Surv. Prof. Paper 157, 1929. Junner, N. R.: Gold Occurrences of Victoria, Australia. ECON. GEOL., vol. 16, p. 104–106, 1921. Todd, E. W.: Kirkland Lake Gold Area. Ont. Dept. Mines, 37th Ann. Rept., 1928. Graton, L. C., McKinstry, H. E., and others: Outstanding Features of Hollinger Geology. Can. Min. Met. Bull., pp. 1–20, 1933. O'Neill, J. J.: The Beattie Gold Mine, Duparquet Township, Quebec. Can. Min. Met. Bull., pp. 299–315, 1934. Spencer, A. C.: The Juneau Gold Belt, Alaska. U. S. Geol. Surv. Bull. 287, p. 34, 1906. Buschendorf, F.: Die primaren Golderze des Hauptganges bei Brandholz im Fichtelgebirge. Neues Jahrb., Beil. Bd. 62A, pp. 1–50, 1931. Junner, N. R.: The geology of the Obuasi Gold Field. Gold Coast Geol. Surv. Mem. 2, 1932.

[35] Lindgren, W.: Mineral Deposits. Pp. 446–447, 1933.

[36] Lindgren, W.: *Idem*, p. 701. Leith, C. K., and Harder, E. C.: The Iron Ores of the Iron Springs District, Utah. U. S. Geol. Surv. Bull. 338, 1908.

[37] Lindgren, W.: *Op. cit.*

[38] Harker, A.: Metamorphism, pp. 83, 255, 1932.

[39] Watanabe, M.: On Adularia and Lamellar Calcite in Contact Metasomatic Deposits. Jour. Geol. Soc. Tokyo, vol. 41, p. 519–532, 1934. Hickok, W. O.: The Iron Ore Deposits at Cornwall, Pa. ECON. GEOL., vol. 28, p. 228, 1933.

formed during mineralization, other equally or more important parts [40] of the total environment in both mineralization and metamorphism are composition of wall rock and temperature.

COMPARISON AND RELATIONS WITH THE TUNGSTEN DEPOSITS.

Scheelite veins have been prospected and mined at several places in the Gold-bearing series. Only negligible, if any, gold values have been reported from them, except possibly at Indian Path, and a close areal relationship with the gold veins is found, so far as the writer is aware, only at Moose River, Malaga, and Oldham.

However, mineralogical and structural similarities [41] to the gold veins suggest some relationship with the gold-bearing mineralization.

The veins are in the Gold-bearing series and are in part parallel to the bedding planes of the sedimentary rocks. They vary up to two feet or so in thickness, and consist mainly of quartz, with some scheelite, carbonate, arsenopyrite and other minerals. The scheelite is chiefly present on or near the walls of the larger quartz veins, or may compose almost the entire filling of small veinlets. It is commonly veined by the highly strained quartz belonging to the main period of quartz introduction, and is one of the earliest minerals to form in the veins. Scheelite is reported from some of the gold veins.

[40] Butler, B. S.: Influence of the Replaced Rock on Replacement Minerals Associated with Ore Deposits. ECON. GEOL., vol. 27, pp. 1–24, 1932. Turner, F. J.: The Genesis of Oliogoclase in Certain Schists. Geol. Mag., vol. 70, pp. 529–541, 1933. See also subdivision of Wissahickon schist. Geologic Map of the United States, U. S. Geol. Surv., 1932.

[41] Based partly on observations and examination of collections made of the veins near Waverley, Indian Path, Scheelite, and one near the Kaulback Gold Mine, Moose River. See also: Messervey, J. P.: Tungsten in Nova Scotia. Ann. Rept. Dept. Pub. Works and Mines, Pamph. 29, pp. 247–264, 1930. Faribault, E. R.: Tungsten Deposit of Moose River, Nova Scotia. Can. Geol. Surv., Summ. Rept., pp. 228–234, 1909. Camsell, C.: Tungsten Deposits of New Brunswick and Nova Scotia. Can. Geol. Surv., Summ. Rept., pp. 247–251, 1917. Goranson, E. A.: Indian Path Scheelite Deposit, Lunenburg Co. Can. Geol. Surv., Summ. Rept., p. 41D, 1931. Piers, H.: On a New Tungsten (Scheelite) Deposit at Tower Sackville, Halifax Co., Nova Scotia. N. S. Inst. Sci., Proc. and Trans., pp. 38–45, 1927.

Wolframite, which varies to hübnerite, is present in all the scheelite veins examined. It is found only as small blades or tabular crystals at most only a few millimeters long. These show a tendency to be concentrated in the quartz near the wall rock. The wolframite has been partly replaced by quartz, and is commonly more or less altered to scheelite. The description of wolframite-hübnerite just given applies also to the occurrences in the gold veins, except that in the gold veins it shows no noticeable association with wall rock.

Ankeritic carbonate is present as a fairly early constituent in all the scheelite occurrences examined, but also some iron-bearing carbonate as well as calcite is later than the quartz.

Tourmaline is not abundant but is present in all the scheelite deposits as small prisms, and foils of muscovite are common in all. A little biotite is present in the veins near Waverley. Apatite as small rounded and corroded grains enclosed in the quartz is similar to its occurrence in the gold veins. Much of the chlorite is vermiculite which forms spreading replacements in crushed quartz adjacent to fractures, and quartz grain boundaries, entirely like its occurrence in many of the gold veins.

Arsenopyrite, the dominant metallic mineral in all of the scheelite veins, is in places massive within the veins and forms enhedral crystals in the adjoining slates, and rarely within the veins as well.

Pyrite is the next most abundant sulphide, with only minor pyrrhotite in the slate wall rocks at Indian Path and Waverley.

Galena is reported as being present at Waverley, but none was seen by the writer.

In summary, the scheelite veins display mineralogical characters quite similar to the Nova Scotia gold veins at the lower temperature limits of the deposits in Zone I.

Scheelite, however, is present only in minor amounts in the gold veins,[42] and gold is generally lacking in the scheelite veins.

[42] Wilson, M. E.: Mineral Deposits in Nova Scotia and New Brunswick. Can. Geol. Surv., Summ. Rept., pp. 77c–91c, 1926. Guide Book No. 1, Pt. 1. Excursion in Eastern Quebec and the Maritime Provinces. Can. Geol. Surv., pp. 171, 196, 1913.

Another difference considering the minerals present is the location of the scheelite deposits at variable distances from the granite intrusives, the veins near Waverley being 1½ miles, those near Scheelite and Moose River 7 miles, and those at Indian Path 13 miles from the intrusive rock.

That the scheelite veins are genetically related to the granite is suggested by the tungsten minerals in tin occurrences in granite and granite pegmatite near Gold River [43] and at New Ross.[44]

It is difficult to explain satisfactorily all these features, but it is considered likely that the scheelite and gold mineralizations came from the same general magmatic source—the granite—but at different times.

According to Piers, the scheelite veins transect gold veins in the Malaga and Oldham districts.[45]

Other regions display relationships between tungsten and gold mineralization, for scheelite is a frequent minor constituent in mesothermal and hypothermal types of gold veins in many places in the world and has been found in recoverable amounts in the gold veins at Macraes Flat-Mareburn, New Zealand,[46] Golden Valley, Southern Rhodesia,[47] and Jardine, Montana.[48]

SUMMARY AND CONCLUSIONS.

Some gold deposits of hypothermal, many of mesothermal, and one group near to epithermal in mineralogical type are found in Nova Scotia. They are in sedimentary and metamorphosed sedimentary rocks, which have been intruded by large masses of granite, and locally by granite and pegmatite dikes.

[43] Davison, E. H.: Tin Lodes in Nova Scotia. Min. Mag., vol. 42, pp. 20–23, 1930.

[44] Faribault, E. R.: New Ross Tin Deposits. Can. Geol. Surv., Summ. Rept., pp. 80–83, 1907. Wright, W. J.: Geology of the Neighbourhood of New Ross, Lunenburg County, Nova Scotia. Can. Geol. Surv., Summ. Rept., pp. 384–389, 1912.

[45] Piers, H.: *Op. cit.*

[46] Williamson, J. H.: Quartz Lodes of Oturehua, Nenthorn, and Macraes Flat, Otago. Jour. Sci. Tech., New Zealand, vol. 16, pp. 102–120, 1934.

[47] Lightfoot, B.: The Larger Gold Mines of Southern Rhodesia. Geol. Surv. S. Rhodesia, Bull. 26, pp. 52–53, (1934).

[48] Winchell, A. N.: Notes on Tungsten Minerals from Montana. ECON. GEOL., vol. 5, pp. 158–162, 1910.

The veins in the districts within one and one-half miles of the large intrusions of granite generally display a group of high temperature minerals, such as garnet, oligoclase, hornblende, biotite, muscovite, tourmaline, epidote, ilmenite, massive pyrrhotite with more rarely molybdenite and andalusite. These high temperature veins also contain most of the minerals present in the numerous districts, which are more than one and one-half miles from the large intrusive masses of granite.

The latter group consists mainly of quartz, carbonate, chlorite, arsenopyrite, and pyrite, with lesser amounts of chalcopyrite, sphalerite, galena, wolframite, and other minerals. Of minor and generally local occurrence only, in some of these districts, are the minerals biotite, tourmaline and massive pyrrhotite. Also, where present in these, the biotite, muscovite and apatite are finer grained than in the high temperature deposits near the granite. The bulk of the gold produced has come from this group, and over one-half the gold from deposits between two and one-half and four miles from the granite, although this area constitutes only about 15 per cent. of the total area of the gold-bearing series of the region shown on the accompanying map.

The gold mineralization at West Gore about 12 miles from the granite contains quartz, albite, carbonate, stibnite, native antimony and small crystals of pyrrhotite. It is near epithermal in mineralogical type.

The gold deposits studied have mineral and structural features in common which indicate that they are a genetic group belonging to one mineralization.

The solutions that formed the gold veins are believed to have come from the granite at depth, and the deposits are zoned to the large intrusive masses of granite, which acted as local heat centers.

Some of the veins near Goldboro, for example, at the Richardson Mine, are of higher temperature type than the veins in the other districts that lie so far from the intrusive rock. An unexposed stock of granite may underlie this district.

Tungsten minerals in small amounts are widely distributed in the gold veins. This fact, when considered with other features,

suggests a genetic relation with the scheelite veins in the same region. The scheelite veins do not form a part of the zoned gold mineralization, and were probably formed either earlier or later than the gold veins.

Oligoclase feldspar is associated with the highest temperature gold mineralizations near the granite. This feldspar and others, with a higher ratio of calcium than albite, are formed, or when present in the wall rocks are stable, in numerous other ore deposits in the world which have formed at high temperature.

Albite is common and worldwide in gold veins throughout the lower temperature part of the hypothermal group and in the mesothermal group.

Similar temperature relations of these feldspars are reported in metamorphic rocks.

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ORIGIN OF THE SOUTHEASTERN MISSOURI LEAD DEPOSITS. PART II.

(Continued from last number.)

W. A. TARR.

ORIGIN OF THE LEAD DEPOSITS.

It will be clearer to the reader if he knows, at this point, the view of the writer as to the origin of these lead deposits. Briefly, it is that moderately hot mineral-bearing solutions rose from below (very probably from some cryptobatholitic igneous mass) and spread out in the sediments, particularly the Bonneterre dolomite, replacing the materials with galena and marcasite. The analysis of the problem (after a brief historical summary) will deal with the source of the metals, their transportation, means of entering the sediments, and cause of deposition. Corroborative evidence will then be presented.

Previous Views as to Origin.

Although these deposits have been known for well over 200 years, little more than incidental reference regarding their origin was made before 1890. It is interesting to note that the first important paper on the origin, that of W. P. Jenney,[1] advocated a magmatic source for the ores, with ingress for the waters through the joints and fissures in the rocks. Owens,[2] nearly 50 years before, had made a similar suggestion concerning the upper Mississippi Valley ores. Whitney[3] had no doubt but that the ores of the Mississippi Valley were of igneous origin. Of the Missouri deposits, he said that as they " have been considerably longer worked, they are now nearer to exhaustion and there is little

[1] Jenney, W. P.: The Lead and Zinc Deposits of the Mississippi Valley. Am. Inst. Min. Eng. Trans., vol. 22, pp. 171–225, 1894 (Discussion, pp. 621–646).

[2] Owen, D. D.: Geological Exploration of part of Iowa, Wisconsin, and Illinois. U. S. Treas. Dept., Washington, 1844.

[3] Whitney, J. D.: Metallic Wealth of the United States, p. 419, 1854.

reason to believe that they will ever regain the importance they once had." Yet 60 years later, they were leading the world in the production of lead. Posepny,[4] in his epoch-making paper on ore deposits, advocates for the southeastern Missouri ores an origin from rising hot waters. Winslow[5] made an exhaustive study of the lead and zinc deposits of Missouri and concluded that the ores originated from "original diffusion through the country rocks and subsequent concentration through surface decomposition of the latter, supplemented by percolating waters." Winslow had the chemist, J. D. Robertson, make a series of analyses of the pre-Cambrian igneous rocks, the Cambrian rocks in which the ores occur, and the Carboniferous rocks. These analyses (given below) showed that small quantities of lead, zinc, copper, and manganese were in all the rocks. Although Winslow concedes that the lead ores of southeastern Missouri are more difficult to explain (than the southwestern Missouri ores), he regards the open texture of the rock and the presence of organic matter (shown by darker color of the rock) as the major factors in the deposition of the ores. From the analyses, he deduces the source of the lead, but utterly ignores the presence of the other metals in his discussion of the southeastern Missouri lead ores and thus exposes the complete weakness of his hypothesis.

Bain, Van Hise, and Adams[6] believe that the first concentration of the ores was accomplished by meteoric waters that had dissolved the metals out of lower sedimentary rocks and then moved upward depositing the sulphides, due to a mingling of solutions and the presence of organic matter. Subsequently, downward-moving solutions produced various changes in the ores. The deposits in the southeastern Missouri area are only briefly mentioned, but their origin is believed to be similar to that of those in southwestern Missouri, rising solutions being especially significant.

[4] Posepny, F.: The Genesis of Ore Deposits. Am. Inst. Min. Eng. Trans., vol. 23, p. 107, 1893.

[5] Winslow, Arthur: The Lead and Zinc Deposits of Missouri. Mo. Geol. Surv., vols. 6 and 7, pp. 467–487, 1894.

[6] Bain, H. F., Van Hise, C. R., and Adams, G. I.: Lead and Zinc Deposits of the Ozark Region. U. S. Geol. Surv. 22d Ann. Rept., pt. 2, pp. 194–195, 203–215, 1901.

Buckley [7] made a detailed study of the deposits, and concluded that the lead was derived from overlying formations (primarily Pennsylvanian; now missing) and was carried downward and redeposited through the effect of organic matter or by means of hydrogen sulphide derived probably as "a result of the action of acids upon soluble sulphides" (CaS is cited as an example). Buckley says (p. 205) that his work produced no evidence that hot solutions or gaseous emanations from below ever saturated or impregnated the sedimentary rocks. He thus disposes of any possible magmatic origin. His paper follows a line of reasoning similar to Winslow's.

Pirsson,[8] expressing dissatisfaction with the meteoric-water theory, suggested, that the deposits may have been formed from the liquid and volatile portions of a magma that rose toward the surface. The same year, Spurr,[9] also, disagreed with Buckley's view, and later [10] very definitely advocated the view that the ores were magmatic in origin. Buehler,[11] 1917, says that their origin is due to "concentration by descending solutions at ordinary temperatures," a view he still holds. In 1918, Tarr [12] reviewed the meteoric-water theories and advocated a magmatic origin for the deposits, a conclusion he had reached for the barite deposits of Washington County, which also contain lead.[13] Emmons [14]

[7] Buckley, E. R.: Geology of the Disseminated Lead Deposits of St. Francois and Washington Counties, Missouri. Mo. Bur. Geol. and Mines, vol. 9, pp. 205–237, 1909.

[8] Pirsson, L. V.: Origin of Certain Ore Deposits. ECON. GEOL., vol. 10, p. 180, 1915.

[9] Spurr, J. E.: Origin of Certain Ore Deposits. ECON. GEOL., vol. 10, p. 472, 1915.

[10] Spurr, J. E.: Ore Magmas, p. 348, 1923, and Southeast Missouri Ore-Magmatic District. Eng. and Min. Jour., vol. 122, Dec. 18, 1926.

[11] Buehler, H. A.: Geology and Ore Deposits of the Ozark Area. Am. Inst. Min. Eng. Trans., vol. 58, pp. 389–408, 1918.

[12] Tarr, W. A.: Genesis of Missouri Lead and Zinc Deposits. Geol. Soc. Am. Bull., vol. 39, pp. 86–87, 1918.

[13] Tarr, W. A.: The Barite Deposits of Missouri. Univ. of Mo. Studies, vol. 3, no. 1, 1916, and The Origin of the Barite Deposits of Missouri. ECON. GEOL., vol. 14, pp. 46–67, 1919.

[14] Emmons, W. H.: Origin of the Deposits of Sulphide Ores of the Mississippi Valley. ECON. GEOL., vol. 24, pp. 221–271, 1927.

has also stated that he believes the lead ores had a magmatic source, but he did not amplify his view. Recently, Dake,[15] in his report on the Potosi (Washington County) quadrangle, argues for the concentration of the lead (and barium) from the surrounding rocks, but presents only the old arguments for this theory.

It is of interest to note the opinion of the origin of these deposits as expressed in various general works on ore deposits. Beyschlag, Vogt, and Krusch[16] interpret the Mississippi Valley ores as being formed by ascending solutions. Niggli[17] regards them as telemagmatic.

Source of the Metals.

The *fundamental* question as to the source of the metals (or elements) in a mineral deposit has been a matter of controversy for 150 years or longer. One group favors a magmatic source; another, the adjacent rocks on *any* side (thus, the meteoric groundwater hypothesis). The list of names in both groups includes the world's leading students of ore deposits.

Source in Surrounding Rocks.—An important mineral deposit unassociated with igneous rocks at the surface would be an ideal example of a deposit derived from adjacent rocks, and hence many have placed the southeastern Missouri deposits in this group. They have advocated the underlying rocks (both sedimentary and igneous), the surrounding rocks for variable distances, and the overlying rocks (now largely removed by erosion) as the source of the metals. To prove that these rocks were a probable source of the ores, analyses were made of the associated igneous and sedimentary rocks. Table I, from Winslow,[18] gives the

[15] Dake, C. L.: Geology of the Potosi and Edgehill Quadrangles. Mo. Bur. Geol. and Mines, vol. 23, pp. 198–219, 1930.

[16] Beyschlag, F., Vogt, J. H. L., and Krusch, P.: The Deposits of Useful Minerals and Rocks, vol. 2, pp. 768–771, 1916.

[17] Niggli, Paul: Ore Deposits of Magmatic Origin, pp. 78–80, 1929.

[18] Winslow, Arthur: The Lead and Zinc Deposits of Missouri. Mo. Geol. Surv., vol. 7, pp. 479–481, 1894.

TABLE I.

AVERAGE LEAD, ZINC, AND COPPER CONTENT OF THREE GROUPS OF MISSOURI ROCKS.

(*J. D. Robertson, analyst.*)

Metal	Igneous rocks (Aver. of 4 specimens)	Cambrian-Ordovician dolomites (Aver. of 6 specimens)	Mississippian limestones (Aver. of 7 specimens)	Average of the 3 groups
Lead	.00397 per cent	.00950 per cent	.00115 per cent	.00487 per cent
Zinc	.00901 " "	.00508 " "	.00104 " "	.00504 " "
Copper	.00614 " "	.00126 " "	.00202 " "	.00313 " "

average percentage of the metals found in three groups of rocks in Missouri.

Buckley states that remarkably high percentages of the metals were found in the Pennsylvanian shales, but he does not give them because he felt that they were so high that they should be confirmed by duplicate analyses.[19] Not many analyses of sedimentary rocks have been made for the traces of metals present, but the few others available are similar in results to those given above. Weems [20] found the average for 9 samples of limestones and dolomite, taken near Dubuque, Iowa, to be .00326 per cent. lead and .00029 per cent. zinc. Clarke and Steiger [21] made analyses of composite samples from which the figures in the following table are taken. Their original percentages of oxides have been converted into those of the metals for ease of comparison with the other analyses. Nickel is included because it also occurs in the Missouri ores.

TABLE II.

PERCENTAGES OF HEAVY METALS IN COMPOSITE SAMPLES.

Metal.	Mississippi River silt (composite of 235 samples)	Igneous rocks (composite of 329 samples)
Lead	.00018 per cent	.00074 per cent
Zinc	.00080 " "	.00510 " "
Copper	.00340 " "	.00931 " "
Nickel	.01330 " "	.00514 " "

[19] Buckley, E. R.: *Op. cit.*, p. 221.

[20] Weems, J. B.: Iowa Geol. Surv., vol. 10, p. 566, 1900.

[21] Clarke, F. W., and Steiger, G.: Jour. Wash. Acad. Sci., vol. 4, p. 58, 1914. See also Clarke: Data of Geochemistry, U. S. Geol. Surv. Bull. 695, pp. 630–633, 1920.

It will be of interest to compare the above analyses of various rocks with the estimates for these elements in the earth's crust, as made by Clarke and Washington [22] and by G. Berg.[23]

TABLE III.

ESTIMATES OF LEAD, ZINC, AND COPPER IN THE EARTH'S CRUST.

	Clarke and Washington's	Berg's
Lead	.002 per cent	.0008 per cent
Zinc	.004 " "	.0060 " "
Copper	.010 " "	.0100 " "

Zies [24] obtained the following values for these metals in a 20-gram sample of the fresh Novarupta rhyolitic glass: CuO, .003 g., PbO, .0004 g., and ZnO, .0016 g. Hevesy and Hobbie [25] show that granitic rocks contain nearly six times as much Pb as basic rocks, a conclusion agreed in by Holmes.[26] In connection with these analyses of rocks, it is of interest to note that McQueen's study [27] of the insoluble residues of the various carbonate rocks in Missouri showed pyrite, marcasite, and, rarely, sphalerite as constituents, but no mention is made of chalcopyrite or galena. Local beds in sedimentary rocks may show many metals, as do the copper shales in Germany [28] although the syngenetic origin of these deposits is questioned by some.

It is common knowledge that all rocks, and even minerals, contain minute quantities of the various metals, and all the above figures are merely in accord with this fact. The question is whether there is any justification for assuming that such percentages represent the actual source of the metals contained in a concentrated, localized, and workable deposit. The traces of

22 Clarke, F. W., and Washington, H. S.: U. S. Geol. Surv. Prof. Paper 127, table 17, p. 34, 1924.

23 Berg, G.: Zeitschr. prakt. Geologie, vol. 5, pp. 73–79, 1925.

24 Zies, E. G.: The Valley of Ten Thousand Smokes. Carnegie Inst. of Washington Pub., no. 693, p. 58, 1929.

25 Hevesy, G., and Hobbie, R.: Lead Content of Rocks. Nature, vol. 128, p. 1039, 1931.

26 Holmes, A.: *Idem*, pp. 1039–1040.

27 McQueen, H. S.: Biennial Report of the Missouri State Geologist, Appendix I, pp. 102–131, 1931.

28 Trask, P. D.: ECON. GEOL., vol. 20, pp. 746–761, 1925.

the metals found in the rocks of the Missouri lead region must represent the amounts *left behind* if the ores were derived from these rocks, yet these traces compare favorably with those estimated for the earth's crust. Moreover, arithmetical computations based on the traces of the metals can hardly be taken as proving the competency of the source of the ores. Nearly 5,000,000 tons of lead have been removed from the mines in the lead belt, and more than double that amount remains underground. The ore is, furthermore, concentrated in restricted areas within a district whose limits are about 6 by 10 miles. Ignoring for the moment such considerations as solution, transportation, and deposition, the formation of about 15,000,000 tons of lead in a very limited area from such minute quantities as those given in the above tables requires an active imagination to vizualize to say the least. If one is to accept as a source of ores the meager quantities of metals possessed by all rocks, why are not workable deposits of all the metals found everywhere? The answer given to this question is always that the other conditions (presumably structure, texture, solvents, and precipitating agents) were not right. But it could also be asked with equal justice, what proof exists that these traces of metals were not introduced into the rocks from a deeper source. It should be noted that the present active ground-water circulation of the mines, with an *abundance* of lead available in the ore deposits, is *not* reconcentrating it into another deposit; is, moreover, having no appreciable effect upon the ore at all.

The position of the source rock relative to the ore deposits is apparently not important in the meteoric-water hypothesis. According to Bain and Van Hise, the solutions acquire the metals below and deposit them on rising; Winslow, Buckley, and Buehler make use of downward-moving (and even laterally moving, as did Siebenthal for the Tri-State area) solutions, and consider all rocks once overlying the ores as possible sources of lead. Secondarily enriched copper deposits are an important source of copper, today, and the process by which they were formed is comparable to Buckley's method for formation of the lead deposits. Yet these copper deposits originated from a deposit with

at least .4 to .5 per cent. of copper, and the Missouri rocks contain only .004 per cent. of lead. Far more copper is left behind in the leached zone of a secondarily enriched copper deposit than occurs in the original rock in the Missouri district. Ransome [29] states that the protore at Ray, Arizona, averaged .4 to .5 per cent. copper, and the leached capping "from a mere trace to .2 per cent." Spencer's figures [30] on the leaching of copper at Ely, Nevada, are as follows. The protore averaged .5 per cent. copper. The average copper content of the material from the surface to the bottom of the overburden (113 feet) was .6 per cent. The lower 43 feet averaged 1.1 per cent. and the upper 70 feet .3 per cent copper. These figures, moreover, are for the metal most commonly subject to secondary enrichment. Spencer expresses the opinion that "about 1/6 of the original copper remains in the finally leached porphyry." Thus, if .08 per cent. of copper, which is readily soluble, remains behind after the leaching process is it probable that the meteoric waters in the Missouri rocks were such effective solvents as to have removed all but such minute traces as .004 per cent. of the very insoluble lead?

The primary source of the materials in sedimentary rocks is the igneous rocks. Normally, the latter should be the richer in metals, but the evidence is contradictory. The values given in the above analyses are actually merely suggestive, as the quantities of the samples (even the composite samples) taken permit of little more than the verification of the presence of these metals in various rocks. They should be regarded as qualitative, not quantitative tests. As suggesting even probable sources for the metals, one is justified in questioning the value of these analyses, and when the other factors involved in forming a deposit are taken into consideration such analyses offer little of real value.

Source in a Magma.—No one knows what the metallic content of a magma may be, but as igneous rocks were derived from magmas their metallic content is a clue to magmatic composition.

[29] Ransome, F. L.: U. S. Geol. Surv. Prof. Paper 115, pp. 157, 159, 165, 1919.
[30] Spencer, A. C.: U. S. Geol. Surv. Prof. Paper 96, pp. 115–116, 1917.

Actually (as the analyses above show), this content does not amount to much. We do know from studies of the earth's probable composition and from the unmistakable association of important ore deposits with igneous rocks that the metallic content of igneous rocks is variable and that locally it may be high. The ore deposits indicate that the method of concentrating the metals in the magma must be highly efficient. As will be noted later, the removal of the metals occurred during the liquid or magmatic stage of the igneous rocks through efficient physio-chemical processes that left the rock impoverished. The metal-rich magmas apparently have had their source in the deeper-lying metal-rich zones (if such exist) within the earth.

Finally, it is not surprising that either igneous or sedimentary rocks should normally be low in metals. The igneous rocks lost most of their metallic content (if they possessed any) during consolidation; and, as the sediments were derived from the igneous rocks, a further reduction in metallic content should be expected in them. It is this sequence of events in the history of the two rock groups that weakens the theory that the metals in the lead deposits came from the weathering or leaching of the associated sedimentary or igneous rocks.

Distribution of Metals in Rocks.

As, under the meteoric-water hypothesis, the metals must be removed by solutions, their distribution within the source rock is an important factor. The assumption is made that the metals were deposited as the sediment accumulated, or as the igneous rock solidified. The metallic salts (land-derived) in the sea water were precipitated (universally assumed as sulphides, but this is not necessary) as the beds accumulated. Normally, the metallic minerals would be disseminated throughout the layer, though rarely some particular one, being abnormally abundant (as the pyrite in the beds in Wabana [31]), might form a bed of the mineral. The distribution of metallic minerals (almost invariably sulphides

[31] Hayes, A. O.: The Wabana Iron Ore of Newfoundland. Geol. Surv. Canada, Mem. 78, 1915.

unless the element can enter a silicate) in igneous rocks is equally one of dissemination. Segregations are already concentrated mineral deposits and hence can scarcely enter into the problem as a source of metals for disseminated deposits although minor local segregations in igneous rocks might contribute some metals. In the main, however, the metals are widely disseminated in igneous and sedimentary rocks alike, and it is these minute grains that the meteoric waters must seek out and remove. This removal hinges upon the permeability of the rocks.

Permeability of the Rocks.

The permeability of the rocks is the factor that must determine how the solutions are to reach and dissolve the very minute grains of metals disseminated through them. Permeability is dependent upon the porosity of the rock. Openings that would permit the entrance of solutions are intergranular spaces of all types, divisional openings (joints and bedding planes), and solution cavities.[32] These factors for the rocks in the lead district will be discussed.

Carbonate rocks may be porous (*e.g.*, chalk) but they are not commonly so. The Bonneterre dolomite has been shown to possess intergranular openings, druses, solution cavities, many joints, and stylolites and related solution features along what were undoubtedly originally bedding planes. Carbonate rocks above the Bonneterre (locally, entirely removed in this district) no doubt possessed similar openings, but not necessarily in the same degree. The druses of the Bonneterre have been shown to be unconnected openings. Very porous dolomites and limestones probably owe their porosity to solution work, the solutions having acted along intergranular faces at first. The highly porous layers in the Bonneterre appear to be largely of this type. The usual openings in carbonate rocks, *i.e.*, the divisional openings due to joints, bedding planes, and stylolites, depend for their spacing upon many

[32] For a discussion of openings in rocks, see Lindgren, W.: Mineral Deposits, pp. 144–153, 1933; and Emmons, W. H.: Principles of Economic Geology, pp. 170–183, 1918.

factors. Near the surface, the openings are numerous, below, they are more widely spaced. Fuller has estimated that the vertical joints in all rocks average from three to seven feet apart and die out rapidly downward. Such a distribution can readily be seen in quarry faces. Solution work along these divisional openings produces enlargement.

Shales (including siltstones) are universally regarded as nonpermeable; confirmed by the fact that they serve as impervious cap and bottom rocks for a porous medium containing either liquid or gaseous substances. As many carbonate rocks are extremely dense and impervious, they, also, may act as cap or bottom rocks. The bedding planes in shales may permit the movement of solutions along them if they are sufficiently open or marked by a coarser material (siltstone layer, for example). Divisional openings do likewise if the shale is rigid enough to maintain the joint. Neither type of these openings permits much circulation of water within a shale. Sandstones, unless cemented, are readily permeable, as is shown by their being common aquifers. They are not, however, a source of metals.

Only capillary or super-capillary spaces permit an active circulation of water in rocks. In sub-capillary spaces, any movement of substances must be by diffusion. The evidence of movement of solutions in carbonate rocks and shales is readily seen in exposures afforded by the innumerable road cuts and other excavations. The penetration of oxidizing solutions to limited distances is very evident, but whoever will carefully examine a joint or other opening in a rock containing sulphides will be surprised to find that the sulphides are unaffected by solutions, even within a fraction of an inch of the joint. J. F. Kemp [33] long ago studied the possibilities of the removal of traces of a metal from a rock, and concluded that water in percolating along a joint could remove only from 1/6 to 1/100 of the total amount present. The smaller figure is probably too high. Actually, solvent effects are confined largely to the walls of the openings. The Bonneterre

[33] Kemp, J. F.: Problem of Metalliferous Veins. Econ. Geol., vol. 1, pp. 207–232, 1906.

dolomite possesses many porous layers, but they appear to have favored the introduction of the metallic minerals rather than their removal.

The openings in an igneous rock are divisional openings, mostly joints. They are numerous in the porphyries of the district, being only a few inches apart. In the granites, they are less common, there being 5–30 feet between the horizontal joints and 1–200 feet between those that are vertical. The porphyries show the action (epidotization) of hot mineralizing solutions which penetrated generally less than an inch from the joints. Cold meteoric waters have accomplished very little, save in the weathered zone, the igneous rocks being impermeable except along the joints. It can be stated positively that meteoric waters did not secure the minerals of the district from the igneous rocks of the region.

Solution of the Metals.

Granting that metals in variable amounts are present in all kinds of rocks, the crucial test of any hypothesis that makes use of them as the source of an ore deposit lies in their solution and removal from the rocks. The composition of the solvent and its ability to penetrate the rock and remove the metals are vital matters that must be discussed. These points, however, have evidently proved to be stumbling blocks to those who have tried to apply the hypothesis that the metals came from the surrounding rocks, if one may judge by their inadequate treatment of the subject. As the solvent under this hypothesis is meteoric water, the writer will make use of this term in contradistinction to "magmatic water," which is regarded as the solvent where the source of the metals is a magma. There is no known method of proving that a certain water belongs to one or the other of these two types, though various lines of reasoning have been applied, and certain constituents have been used by geologists to draw probable lines between them. It is desirable to know the probable type of water as there is believed to be a marked difference in the relative efficiency of the two waters to dissolve and transport metals. The character of a mineralizing water can only be deduced from the

presence of certain minerals in a deposit and the character of the changes induced in the country rock at the time the deposit was formed, since the water itself has long since escaped. It is the need of information about mineralizing solutions that makes Zies' work in the Valley of Ten Thousand Smokes so valuable.

Meteoric Waters.—Meteoric water is normally cold. It is never pure since it contains various acids, gases, and dissolved salts. These constituents differ in their influence upon the solvent ability of the meteoric water. Although generally regarded as descending waters, they may move not only downward but also laterally or upward. In fact, some hold the view that meteoric waters may sink far enough below the surface to become hot (a doubtful proceeding), or may come in contact with still hot igneous rocks and thus become heated. The latter is very probably true for the hot springs in Arkansas.[34]

Normal meteoric waters are carbonate waters, and undoubtedly those in the lead belt were such because dolomite is the country rock. Carbonate waters are weak solvents. Other meteoric waters are sulphate or chloride in character, but the geology of the district is opposed to the possibility of there being waters of those types present. Hydrogen sulphide is present in some meteoric waters, but not commonly. The world-wide study of spring waters (excellent examples of meteoric waters that might be carriers of metals)[35] and well waters from thousands of feet below the surface has revealed little evidence that such waters are effective solvents of the metals.

The ability of meteoric waters to dissolve the various metals involved in the lead deposits must be weighed and considered. Apparently, most of the men who favor meteoric waters as the solvent have no doubt as to their ability as such, since they state simply that the metal was taken into solution and carried downward, or in some other direction. What are the facts? The solubilities of the salts of the common metals found in the lead deposits are given in Table IV:

[34] Bryan, Kirk: Hot Springs of Arkansas. Jour. Geol., vol. 32, p. 449, 1924.

[35] Clarke, F. W.: Data of Geochemistry. U. S. Geol. Surv., Bull. 695, pp. 175–211, 1920. Lindgren, W.: Mineral Deposits, pp. 41–73, 1933.

TABLE IV.

SOLUBILITY TABLE.[1]

Compound	Grams soluble in 100 cc. of water	
	Cold water	Hot water
Lead sulphide (PbS)	.000086 at 18° C.	insoluble
Lead sulphate ($PbSO_4$)	.0028 at 0°	.0056 at 40° C.
Lead carbonate ($PbCO_3$)	.00011 at 20°	decomposes
Lead chloride ($PbCl_2$)	.673 at 0°	3.34 at 100°
Lead fluoride (PbF_2)	.064 at 20°	
Zinc sulphide (ZnS)	.000065 at 18°	insoluble
Zinc sulphate ($ZnSO_4$)	49.4[2] at 0°	86.5 at 80°, 80.8 at 100°
Zinc sulphate ($ZnSO_4 \cdot 7H_2O$)	115.2 at 0°	663.6 at 100°
Zinc carbonate ($ZnCO_3$)	.001 at 15°	insoluble
Zinc chloride ($ZnCl_2$)	432.0 at 25°	615 at 100°
Copper sulphide(ous) (Cu_2S)	.0005 at 18°	
Copper carbonate (all forms)	insoluble	insoluble and decomposes
Copper sulphate ($CuSO_4$)	14.3 at 0°	75.4 at 100°
Copper chloride ($CuCl_2$)	70.6 at 0°	107.9 at 100°

[1] Data from Handbook of Chemistry and Physics, 1933.
[2] Olsen's Chemical Annual, pp. 438–439, 1926.

Data such as in Table IV serve mainly to indicate what might be expected, as it is unknown how much influence other substances in a solution might have on the final product. The relationship of the field evidence to the facts given in the solubility table will be examined.

Lead sulphide is indicated as being extremely insoluble, and the field evidence amply bears this out. Every lead deposit in the Mississippi Valley was discovered by finding *residual galena* at or near the surface. The original country rock had been removed, leaving behind the most insoluble materials—clay, iron oxide, and the galena, most of which still retained its cubical form. Evidence of solution work is to be seen in the rounded edges on the cubes, or the pits (representing very possibly an inclusion that was soluble) on their surfaces. That some galena had passed into solution is shown by the presence of cerussite and anglesite, but the quantity of these two minerals is small. To the writer's knowledge, no one has ever proved that secondary galena has been formed in a lead deposit. The galena and its two insoluble oxidized compounds, cerussite and anglesite, are left behind if the associated metals in the deposit do move elsewhere. Of these

two, the carbonate is the usual one formed in the Missouri lead district because the ores occur in a carbonate rock. A thin layer of lead sulphate may be formed on the galena,[36] but it soon changes to the more insoluble carbonate.

How long these galena crystals have been subjected to the attack of meteoric waters is only conjectural. Probably since the early part of the Tertiary, if not longer. It can scarcely be doubted, however, that galena in overlying formations (where present) would be similarly concentrated at the surface instead of being carried downward. It is improbable that it would be leached (due to the great insolubility of the two oxidized lead salts) from the Pennsylvanian beds and then become a residual deposit from a lower formation. The absence of lead in residual soils over Pennsylvanian or Mississippian beds (which showed traces of lead) in the face of its great insolubility suggests that it was never present in the original rock.

Thus not only is the insolubility of galena opposed to its being removed in solution by meteoric waters, but the geological evidence indicates that it is left behind as a residual deposit. Couple this insolubility of galena with the inaccessibility of the traces of it found in the rocks, and the possibility that meteoric solutions could gather millions of tons of lead and concentrate them into the rich deposits of the southeastern Missouri district becomes extremely remote, if not impossible, even though there was ample geological time available.

The other common metals associated with the lead in the deposits, though small in amount, should be considered. The analyses made of the rocks to determine the source of the lead showed the presence of zinc and copper also. The quantity of zinc slightly exceeded that of lead—Zn = .0050%, Pb = .0048%. Copper was less in amount than either, being .0031%. It should be noted that in the percentages given for the metals in the earth's crust those for copper exceeded those for zinc and the amount of zinc exceeded that of lead.

[36] Swartzlow, C. R.: Alteration of Galena to Anglesite to Cerussite. Am. Min., vol. 18, pp. 174–175, 1933.

The common zinc sulphide, sphalerite, is insoluble, as shown in the table. The field evidence confirms this, in part, as sphalerite occurs, along with the galena, in residual deposits. However, $ZnSO_4$ does form (from the sulphide), and as it is readily soluble it is removed, exposing a fresh surface of the sulphide to the oxidizing solutions. In the presence of carbonate solutions, the $ZnCO_3$ forms and, being relatively insoluble, is found in zinc deposits. Furthermore, if pyrite or marcasite is present along with the sphalerite, their oxidation produces sulphuric acid that attacks the ZnS and removes it. In explaining the concentration of the lead by meteoric waters, investigators have ignored the zinc (Buckley suggests that the analyses for zinc may have been wrong, though why they should be wrong more than those for lead is not explained), even though it is more than equal to the lead in quantity. Lead and zinc ores deriving from the same source occur in the deposits in southwestern Missouri, so the absence of zinc ores in the lead deposits of southeastern Missouri must be explained.

Copper was also present in the original rocks of the district, and like zinc, it is readily soluble as a sulphate, as is proved by the occurrence of innumerable secondarily enriched copper deposits. Yet like the zinc, copper is not considered in the accounts of the origin of the lead deposits. The two metals, zinc and copper, which *can* be transported by meteoric waters are ignored by the proponents of the meteoric-water hypotheses, but the insoluble lead is moved about easily! Making use of the lead content of the rocks while ignoring the presence of the other two metals (though uncommon in the deposit) is hardly a scientific procedure. For the deposits of southwestern Missouri, in which zinc occurs but no copper, Buckley, Buehler, Bain, Van Hise, Siebenthal, and others ignore the copper, but make use of the data for lead and zinc. That neither the copper nor zinc could have been completely removed by meteoric waters is proved by the evidence in many other deposits where these elements occur together. This attempt at selectiveness (further unfortunate in making use of the most insoluble metal) on the part of the ad-

vocates of the meteoric-water hypothesis clearly indicates the inadequacy of the theory.

Cobalt and nickel were not determined by Robertson in his analyses of the various Missouri rocks, and, aside from their sulphates, salts of both the metals are generally insoluble. As all known cobalt and nickel ores are normal magmatic deposits, they will not be discussed here.

Magmatic Waters.—The study of water (liquid and gaseous) associated with lavas and volcanoes has been the chief (and important) source of information about magmatic waters, but this has been supplemented by deductive studies of ore deposits of undoubted magmatic origin. The dominant gas emitted from volcanoes is water vapor, which is, of course, soon condensed to a liquid form. The "Ten Thousand Smokes," in the Alaskan valley of that name, are the result of such condensation. But emitted along with the water vapor are many other gases some of which, such as chlorine, hydrochloric acid, hydrofluoric acid, carbon dioxide, sulphur dioxide, hydrogen sulphide, hydrogen, and oxygen, are important aids in mineralization. Zies [37] found that the fumaroles in the Valley of Ten Thousand Smokes contained both hydrochloric and hydrofluoric acids and hydrogen sulphide, and, what was very significant, chlorides and fluorides of iron, lead, zinc, copper, and other metals. He found that the gases had the very high temperature of 650° C.—a higher temperature than that needed to volatilize the chlorides and fluorides of many of the metals.

Due to their wide range in temperature, various active solvents, and the ability to permeate all parts of a liquid magma, magmatic solutions must be regarded as far superior to meteoric waters in solvent action.

Transportation of the Metals.

Transportation of the metals is an essential step in the formation of ore deposits. It involves movement of solutions and this hinges upon permeability of the rocks. The character of the

[37] Zies, E. G.: The Valley of Ten Thousand Smokes. Nat. Geog. Soc., Geophysical Lab., no. 693, 1929.

openings in the rocks (as discussed above) indicates that, as far as the dolomite is concerned, movement, though possible, is confined primarily to the divisional openings. There appears to be no restriction of free movement along these openings.

By Meteoric Waters.—In meteoric waters, the metals must be transported as sulphates or carbonates. Only zinc and copper sulphates are readily soluble and they are present in the ores only as minor elements. The carbonates of these metals are soluble with difficulty, and *both* these salts of lead are very insoluble. The possibilities of transporting the lead as the sulphate or carbonate, therefore, appear to be remote, and there is no reason for assuming that the lead (or other metals) were transported as other compounds.

Under the meteoric-water theory, transportation is a vital consideration, as the lead must be collected from the surrounding rocks and carried to the site of the present deposits. How large an area was necessary as a collecting ground, none of the advocates of this theory have postulated. If the lead of the district was concentrated only from overlying rocks (Pennsylvanian, for example), it should have been able to form an ore body in *any* rock beneath. So the question as to why there was so much lead in the Pennsylvanian rocks is pertinent. Stating only that lead was derived from overlying rocks is merely begging the question as to its origin; and if the waters had to search a wider area for the lead, why did the solutions converge in local spots in the lead belt? They probably came from many miles away, and if so what were the structural factors that controlled their movement? Buckley suggests that a part of the lead-bearing solutions may have risen from the La Motte, but argues that the lead was carried down into the La Motte from above, a seemingly unnecessary if not impossible route.

By Magmatic Waters.—Magmatic emanations (gaseous and liquid) offer much greater possibilities of transportation, particularly of lead, than do meteoric waters. Their solvent power is heightened not only by their higher temperature, but also by the presence of active hydrochloric and even hydrofluoric acids.

Among all of the lead salts possible in either type of solution (as far as is known, at present), the chloride is the most soluble. Chlorides of zinc and copper are also very soluble, as are these salts of cobalt and nickel. It appears improbable that the temperature of the magmatic solutions was ever high enough to permit them to carry any volatile compounds; $PbCl_2$ melts at 501° C.,[38] for example, hence its vapor pressure is still higher. This is clearly shown in Figure 3 in Kristofferson's paper.[39]

The magmatic solutions in rising from below would make use of the major joints and water channels (if present), as well as any other divisional openings in the dolomite. If they rose from restricted areas, they could carry their mineral content into the overlying rocks and give rise to ore bodies. Instead of concentrating their metallic content, the magmatic solutions, as they spread out, actually disseminated it through the rock.

Deposition of the Ores.

By Meteoric Waters.—Under the meteoric-water theory, the lead was precipitated as the sulphide from oxidized salts. It was supposed that this was accomplished dominantly through reduction of the sulphate by carbonaceous or bituminous matter, a prevailing concept some years ago but now largely discarded by a majority of the students of ore deposits. The simplicity of the concept was attractive. Carbon (from organic matter), always supposed to have an inherent attraction for oxygen, was believed to have removed the oxygen from the strong sulphate radical leaving the sulphur free to combine with the lead (or other metal). For example, it was thought that C would react with $CaSO_4$ and water, forming H_2S and $CaCO_3$, and that the H_2S would then precipitate the galena from $PbCO_3$ (the form in which the lead was assumed to have been transported) in either moderately acid or alkaline solutions.[40] Other sources of H_2S

[38] Handbook of Chemistry and Physics, pp. 324–325, 1933.

[39] Kristofferson, O. H.: Hydrothermal Experiments with Lead and Zinc Minerals. ECON. GEOL., vol. 31, pp. 185–204, 1936.

[40] Buckley, E. R.: Disseminated Lead Deposits of St. Francois and Washington Counties, Missouri. Mo. Bur. Geol. and Mines, vol. 9, pt. 1, p. 237, 1909.

were suggested, a common one being the oxidation of iron sulphide, or some soluble sulphide such as CaS (not known to exist on the earth except in specimens of meteorites). The inadequate source of the lead, its inaccessibility in the original rocks, and its insolubility are all factors difficult of explanation in the formation of the lead deposits under the meteoric-water hypothesis, and accounting for the necessary sulphur adds to the difficulty of the problem.

By Magmatic Waters.—Under the magmatic theory, it is assumed that, since sulphur is always, in some degree, associated with volcanoes, it certainly occurs in the magmatic solutions. Sulphide compounds are almost universal in metallic mineral deposits associated with igneous rocks. With sulphur (normally as H_2S, but also in other forms) available in the solutions or rocks, the precipitation of the galena would occur when or where the lead salt could react with the H_2S. Some indication of the amount of H_2S that might be present in a magma may be gained from the fact, determined by Zies,[41] that in the Valley of Ten Thousand Smokes 9,300,000 tons of H_2S are present in the gaseous emanations in one year. This amount of H_2S would precipitate about 65,000,000 tons of galena, or more than four times the amount of the Missouri ores, both those removed and the estimated reserves.

Furthermore, the position of the Missouri ore bodies, *i.e.*, in the lower part of the Bonneterre dolomite (Fig. 15), and the presence in them of certain hydrothermal minerals, indicate rising hot (or very warm) waters as the depositional agent.

Conclusions Obtained by Contrasting the Meteoric-water and Magmatic-water Theories.

It is concluded from the foregoing discussion that:

1. It is improbable that the rocks surrounding the lead ores could have supplied the amount of lead present in the deposits, whereas known lead deposits of magmatic origin indicate that a magma would have been a far more feasible source.

[41] Zies, E. G.: The Valley of Ten Thousand Smokes. Nat. Geog. Soc., Tech. Series, vol. 1, p. 46, 1929.

2. If the lead came from overlying rocks only, it probably originally existed there as an important ore deposit, and hence the primary source of the lead is still unexplained.

3. Even though distributed through the original rocks, the scattered grains were inaccessible to meteoric solutions, because,

4. The solutions were confined dominantly to the divisional openings.

5. Meteoric waters are cold, dominantly carbonate, and, on the whole, poor solvents; whereas magmatic waters are hot and contain strong acids and gases that make them efficient solvents.

6. Magmatic waters in permeating all parts of a liquid magma could acquire a metallic content that varied with the magma.

7. Oxidized lead salts are all very insoluble, whereas lead chloride (a possible constituent of magmatic waters) is soluble.

8. The other metals, zinc and copper, were shown by Robertson's original analyses to be present in the rock, and, though more soluble than the lead, were ignored in the explanation of the origin of the ores.

9. The transportation of large quantities of the insoluble lead salts by meteoric waters is improbable, although in hot magmatic waters the lead could be transported.

10. The advocates of the meteoric-water theory found it impossible to accomplish the deposition of the ores without the use of H_2S; and H_2S is much more abundant and effective in magmatic waters.

The Author's Hypothesis.

The source of the metals was in a magma that occurred probably within several thousand feet of the surface, but which apparently had several cupolas that penetrated nearer the surface—possibly one under each of the separate districts. The magma was a part of the metallogenetic province of the Mississippi Valley, which was remarkably free from the precious metals but rich in the base metals (lead, iron, zinc, and, to a less extent, copper) and the minor metals (notably cobalt and nickel, in southeastern Missouri; cadmium and traces of rarer elements, in the Tri-

State area; and mercury, in Arkansas). Only in the southeastern Missouri area did the lead occur virtually alone.

Solidification of this magma resulted in the segregation of the solutions as the silicates developed into igneous rocks. Along with the solutions went any soluble metallic compounds present, as well as various gases, notably H_2S, fluorine, and doubtless chlorine. In one area in the Mississippi Valley (*i.e.*, the fluorspar district of Illinois and Kentucky to the southeast of the Missouri lead belt), the fluorine became fixed as fluorite. It is unfortunate that chlorine does not form a relatively insoluble compound which can be deposited, so as to indicate its former presence. However, there have been reports [42] of finding NaCl in cavities in the galena of the Missouri district, although the writer has been unable to verify this in a single specimen. The magmatic solutions carried the lead, probably, as the chloride and, less probably, as the fluoride.[43] The cupola in the Mine La Motte-Fredericktown area contained cobalt, nickel, and copper in greater amounts than they are found in the lead belt, but the presence of these metals in the latter area proves an original connection. The Washington County barite area was underlain by a barium-rich cupola. The reason this area contains so much barite may be because barium can be carried farther than lead (or the other metals) due to the marked solubility of $BaCl_2$, as the deposits of this district are the farthest removed, stratigraphically, from the magma. Barite may have been present in the formations over the deposits of the lead belt, though this appears to be doubtful since no barite occurs with the ores.

The solutions rose along joints (faults?) in the pre-Cambrian igneous rocks (Fig. 15–*A*). Apparently, these joints were not the present-day faults, which show no evidence of mineralization, but more probably were joints (and faults) or even shattered

[42] Head, R. E.: Am. Min., vol. 16, pp. 345–351, 1931. Buerger, M. J.: Am. Min., vol. 17, pp. 228–233, 1932. Newhouse, W. H.: ECON. GEOL., vol. 27, pp. 419–436, 1932.

[43] Fenner, C. N.: Pneumatolytic Processes in the Formation of Minerals and Ores. The Ore Deposits of the Western United States, pp. 58–106, 1933. Zies, E. G.: The Valley of Ten Thousand Smokes. Nat. Geog. Soc., Tech. Series, vol. 1, no. 4, 1929.

zones in the igneous rocks now buried under the ore bodies. These joints may have been somewhat parallel to the present faults (suggested by the Leadwood-Bonneterre alignment parallel to the Big River fault and the Leadwood-Flat River alignment parallel to Simms Mountain fault) but there is no proof of this. The ore solutions were fed into the La Motte sandstone, and from it into the Bonneterre dolomite. This occurred mainly over or around buried hills of pre-Cambrian igneous rocks, or at anticlinal joints in the La Motte-Bonneterre contact. Mr. Wagner suggests that the major faults in the igneous rocks branched near the surface, and that as the solutions rose along the Simms Mountain fault they followed each successive branch upward.

Major joints (trending N. W. and including present water channels) furnished the mode of ingress to the Bonneterre dolomite (Fig. 15–*B*). In this formation, the other system of joints (rudely at right angles) enabled the solutions to spread laterally, as well as vertically, from the main feeders (Fig. 15–*B*). From these joints, the solutions spread along the stylolites, stylolitic seams, solution planes (originally bedding planes, in part at least), and porous beds of dolomite. It is believed that H_2S found its way into the body of the dolomite first (had the lead chloride been first, it would have formed $PbCO_3$ by reaction with the dolomite, as was demonstrated in the laboratory), and that it saturated the porous beds to a greater or less degree, as well as occupied the minor joints which had developed during various periods of movement since the Cambrian. The remarkably disseminated galena, independent of any opening *within a bed,* is indicative of the penetrating ability of the H_2S and the metal-bearing solutions.

The lead is believed to have come in largely as the chloride, and to have reacted with the H_2S and deposited PbS. This was demonstrated experimentally with tubes of powdered dolomite, as well as the solid rock. In the absence of H_2S, $PbCO_3$ was formed by reaction with the dolomite, the Ca–Mg going off as chlorides. Newhouse [44] suggests that the sulphur was introduced as Na_2S which then reacted with the $PbCl_2$ to precipitate the

[44] Newhouse, W. H.: *Op. cit.*, p. 434.

galena, basing his reaction on the presence of NaCl in cavities in the galena. His tests revealed, also, $CaCl_2$ but not $MgCl_2$. Inasmuch as the galena replaced dolomite, the absence of Mg (or even its presence in traces) among these chlorides is difficult of explanation, especially in view of the fact that the same elements were found in all specimens, even those from very different types of deposits.

The $PbCl_2$ or $FeCl_2$ reacted with the H_2S to form the sulphides of galena or marcasite respectively, and the resulting HCl in dissolving parts of the dolomite (which thus permitted replacement) formed Ca and Mg chlorides. As no $PbCO_3$ appears in the ores (save the secondary $PbCO_3$), there must have been an excess of H_2S in all parts of the dolomite penetrated by the lead solutions. The temperature (between 100 and 150° C.) was low enough to permit the H_2S to exist.[45] The solutions were dominantly acid throughout the time of ore deposition, but may have become neutral or slightly alkaline at its close. The solutions were not oxidizing in character at any time during deposition, or since, save where the present surface waters penetrate this dolomite.

The paragenesis of the ores shows that marcasite was deposited first, followed by the cobalt, nickel, copper, and even zinc sulphides (if any of them were present in the solution), with galena normally last. The optimum for the deposition of marcasite is an acid solution at temperatures of 110–118° C.[46] The introduction of the $FeCl_2$ probably occurred at higher temperatures than those for the succeeding minerals, but not markedly higher or the H_2S would have been oxidized and the optimum for marcasite been exceeded.

An interval of time elapsed before the other minerals were deposited. The conditions most favorable for the deposition of the cobalt-nickel-copper sulphides are not positively known, but Zies[47] found traces of all of them, as well as zinc, along with the lead sulphide in various fumarolic deposits in the Valley of Ten Thou-

[45] Zies, E. G.: *Op. cit.*, p. 46.

[46] Allen, E. T., Johnson, J., Crenshaw, J. L., and Larsen, E. S.: Am. Jour. Sci., vol. 33, p. 169, 1912. Lindgren, W.: Mineral Deposits, p. 830, 1933.

[47] Zies, E. G.: *Op. cit.*, pp. 19 and 33.

sand Smokes, hence they are evidently deposited under conditions similar to those for the lead sulphide. As the quantity of these minerals in the lead ores proper is so small and they are so scattered throughout the mines, the assumption may be made that local (though unknown) conditions controlled their deposition. At Fredericktown and Mine La Motte, the ore solutions were certainly richer in these Co-Ni-Cu sulphides than elsewhere. The La Motte sandstone acted as their depositional site, the sulphides being deposited in the interstices of the sandstone and also replacing it. The ores at Fredericktown are associated with a buried porphyry hill that cuts the sandstone and penetrates the Bonneterre dolomite for more than 240 feet. The solutions were trapped around this hill (Fig. 16), depositing most of the metals on the south and west sides. At Mine LaMotte, an anticlinal roll in the sandstone formed a similar trap for the solutions. Siegenite is normally first, but chalcopyrite may overlap or replace it, rarely, chalcopyrite may be first, or each may occur alone. The two minerals were evidently closely associated, chemically, in the solutions, but siegenite was deposited at a slightly higher temperature.

Sphalerite is generally associated with the Co-Ni-Cu minerals, but not in all cases. It is probably more common than the inspection of the ores suggests, as zinc is the most abundant element, after the lead and iron, in the concentrates. It may replace any of the preceding sulphides, as well as all other minerals. At the Missouri Cobalt Mine in which sphalerite is abundant, it also replaces galena, whereas in the lead belt the galena is last and may replace the sphalerite.

The galena, as has been stated, is normally last. In the ores in which marcasite and galena dominate, it rarely replaces the marcasite, but if the two are in contact is molded on it. The galena occurs dominantly in dolomite, replacing all materials and filling cavities. It developed in any place where the lead solution found H_2S. The lead solutions and H_2S permeated and saturated the dolomite, following porous beds, joints, and stylolites and other solution cavities. Fed by the major joints to the cross

joints, there was ample opportunity to reach every permeable bed. Texture (medium- and coarse-grained beds were favored), porosity, and the number of stylolitic seams were determining factors in this distribution, and not the presence of a certain color or of carbonaceous material.

The ore-bearing solutions not only replaced the dolomite with ore minerals, but also altered it through bleaching and recrystallization. The alteration of the dolomite ends with the ores, which shows that it was the ore solutions that produced it. The dolomite with the ores was not always altered, showing that the character of the solutions must have been different in different places.

The solutions that deposited the ores are believed to have had a temperature of 125° C. or less. The presence of abundant marcasite indicates a temperature of about this value. Newhouse,[48] from his study of the gaseous inclusions of sphalerite, concluded that the ores of the Tri-State area were deposited at temperatures of 115 to 135° ±, and those of the Wisconsin-Illinois-Iowa region at 80 to 105° C. If the Co-Ni-Cu-Zn sulphides were deposited at a higher temperature than the marcasite, it was probably due to the fact that the solutions depositing the marcasite had heated up the rocks and so the solutions that followed did not cool so rapidly. The general zonal distribution of ores indicates that galena was one of the last minerals deposited, and generally at a temperature around 100° ± C. Further confirmatory evidence of the maintenance of some such temperature (or even a higher one) is found in the fact that deposition of the silicate, dickite, followed the sulphide deposition.

Dickite was deposited last in cavities in the sulphide ores and, more rarely, in cavities in the dolomite. Dickite is known as one of the rarer varieties of the kaolin minerals, and it was the recent thorough study by Ross and Kerr [49] that determined not only its position within the group, but also the conditions of its forma-

[48] Newhouse, W. H.: Temperature of Formation of Mississippi Valley Lead-Zinc Deposits. ECON. GEOL., vol. 28, p. 744, 1933.

[49] Ross, C. S., and Kerr, P. F.: The Kaolin Minerals. U. S. Geol. Surv., Prof. Paper, 165–E, 1931.

tion, which are by moderately hot solutions. Evidence is rapidly accumulating, however, that dickite is a common constituent of many ores, especially those recognized as shallow- but hot-water deposits.[50] The presence of dickite in the lead ores of southeastern Missouri was discovered during this study, and is regarded as of much genetic significance and in keeping with the other data relative to the associated minerals. It was apparently deposited during the closing stages of mineralization, but by solutions that were still hot.

As the mineralization ceased, dolomite crystals, some pyrite (indicating a change to neutral or alkaline conditions), and rarely quartz crystals were deposited. Mineralization was brought to a close with the deposition of the calcite in veins and cavities. Rarely, a little galena was deposited along with the calcite. It is not impossible that some of the calcite veins are earlier than the chief ore mineralization, as evidence was found that galena had replaced a calcite vein that crossed an ore bed. Since the mineralization, ground-water solutions have been actively engaged in dissolving the dolomite along stylolites, stylolitic seams, and solution planes, as will be described in detail below.

Thus, it will be seen that the location of the ores is primarily due to structural features, but that these features coincide with the cupolas of a cryptobatholitic magma [51] below, from which the hot metal-bearing solutions and gases rose through the jointed and faulted pre-Cambrian igneous basement rocks into the La Motte sandstone, which fed the solutions into the Bonneterre dolomite. The joints in the Bonneterre led these solutions upward. The solutions were richest in H_2S gas over any anticlinal feature of the underlying rocks. The solutions, in rising, spread laterally along such members of the Bonneterre as offered ade-

[50] Tarr, W. A., and Keller, W. D.: Dickite in Missouri. Am. Min., vol. 21, pp. 109–114, 1936.

[51] Niggli (Ore Deposits of Magmatic Origin, p. 79, 1929) states that the Mississippi Valley deposits "are apomagmatic in the true sense of the word." Graton (Ore Deposits of the Western United States, p. 194, 1933) classes them as "telethermal" to indicate "their direct affiliation with the hydrothermal family."

quate porosity and divisional openings, or became disseminated throughout extensive areas of the dolomite that was sufficiently permeable. Solutions penetrated the entire thickness of the Bonneterre dolomite, but the workable ores are essentially all confined to the lower 270 feet. All of the metals were transported primarily as chlorides (but possibly also as other salts) and were precipitated by reaction with H_2S. In the relatively recent water channels, not much change in the ores has been produced, the action being confined to that of minor oxidation of the dolomite along the channels (prominent horizontal joints) and slight attacks upon the sulphides.

Time of Mineralization.

The evidence as to when the southeastern Missouri ores were deposited is meager; certainly they can be said to be post-Cambrian. The Tri-State ores (as well as the few central Missouri ores) are certainly post-Pennsylvanian. The fluorspar deposits of Illinois and Kentucky are post-Carboniferous and probably late Cretaceous. Igneous dikes cut the Cambrian rocks in the southeastern Missouri area; in fact, these dikes occur between, but slightly to the east of, the mineralized areas of St. Francois and Madison counties. One of these dikes has been proved to be of Devonian age,[52] and Weller regards the nearby dikes as probably of late Cretaceous age.[53] The dikes in Arkansas have been shown by Miser and Ross [54] to be probably Upper Cretaceous. The fluorspar deposits are believed by Bain [55] to be pre-Tertiary. Spurr,[56] in 1923, regarded them as post-Cretaceous, but in a later paper [57] places them near the close of the Cretaceous.

Dating the mineralization near the end of the Cretaceous would place it in a widely recognized metallogenetic period,[58] and also

[52] Tarr, W. A., and Keller, W. D.: *Op. cit.*, p. 823.

[53] Weller, S., and Leclair, S.: *Op. cit.*, p. 249.

[54] Miser, H. D., and Ross, C. S.: U. S. Geol. Surv., Bull. 735–I, p. 312, 1923.

[55] Bain, H. F.: U. S. Geol. Surv., Bull. 255, p. 26.

[56] Spurr, J. E.: The Ore Magmas, vol. 1, pp. 401 and 412, 1923.

[57] Spurr, J. E.: The Southeast Missouri Ore-Magmatic District. Eng. and Min. Jour., vol. 122, no. 25, p. 4, 1926.

[58] Lindgren, W.: Mineral Deposits, p. 890, 1933.

make it coincide with diastrophic movements that evidently occurred at that time throughout the Mississippi Valley, as well as elsewhere. The intrusion of the basic dikes may have preceded or followed the major ore mineralization. It is of interest to note that a minor deposit of galena, sphalerite, pyrite, marcasite, chalcopyrite, and calcite is associated with a basic dike near Avon, St. Francois County, Missouri.[59] Whether this mineralization accompanied the dike or was later is a question. Ball thinks it followed the injection closely. Singewald thinks it was much later. The author agrees with Ball.

There seems to be little evidence for believing that the ores of southeastern Missouri were formed during the Tertiary which was an era of peneplanation marked by a slight arching of the peneplain toward the close of the period. Late Cretaceous appears to be the most probable age of the ores.

Subsequent Changes.

It was noted above that essentially no change in the mineralogical character of the ores has occurred since they were deposited. The marcasite and chalcopyrite, two relatively easily altered sulphides, are perfectly fresh throughout the mines. More changes have occurred since the mines were opened than had occurred in the long geological period that preceded.

This study has revealed, however, that an enormous amount of solution work has gone on in the dolomite, manifested chiefly by the presence of numerous stylolites, stylolitic seams, and other solution planes. The details of these features have been given, but their geological significance must be noted here. Their great number indicates that much dolomite has been removed in solution. These features were initiated as soon as the Cambrian sediments become solid, and were developed in marked degree by the end of the Paleozoic era. It is not known whether the Missouri region was submerged during the Mesozoic era, but probably it was not, at least, not all of the time. If not, there was time

[59] Ball, S. H., and Singewald, J. T., Jr.: An Alnoite Pipe, Its Contact Phenomena, and Ore Deposition near Avon, Missouri. Jour. Geol., vol. 38, pp. 456–459, 1930.

for additional solution work in the rocks. The ore-bearing solutions followed the same means of entrance that the ground waters had been using, hence the ores are associated with stylolitic features of all sorts.

During the long period of erosion and peneplanation of the Tertiary period, the ground-water solutions were busy removing additional dolomite along the previous stylolitic features. Stockdale [60] has shown that from 30 to 40 per cent. of a carbonate rock may be removed in the development of these solution features. During the process, entire beds disappear, and if the solvent action is of unequal rate at different points an apparent unconformity may develop. This has happened in the Bonneterre dolomite (Figs. 5 and 18). Some beds curve over rolls in the rocks below (Fig. 5), but examination reveals that the usual residual band and the stylolites in the underlying beds are horizontal. Changes in dip through the removal of whole beds (Fig. 17) are not uncommon.

The net result of this solution work has been to *reconcentrate* the galena and other sulphides (along with the residual clay). The process has produced a type of secondary residual enrichment not hitherto recognized in ore bodies. The innumerable stylolitic seams associated with the ore, the galena in the residual clay, the crushed character of the galena along well developed stylolites, the curving of the residual clay bands around the sulphides (little galena ever crosses them), and the undissolved patches of dolomite (commonly with included metasomes or metacrysts of galena or other sulphides) included in the residual clay all offer indisputable proof that extensive solution work has occurred. This solution process has greatly aided in the production of the excellent grade of ore in the district for in some places the entire bed of dolomite has been removed. A fine example of enrichment (Fig. 18), is to be seen in stope 4,587 of the St. Joseph Lead Company's mine No. 16. The ore has from one to four inches of dark residual clay both above and below it. At the end of the ore body, the beds thicken in about 100 feet to their orig-

[60] Stockdale, P. B.: Jour. Geol., vol. 34, p. 406, 1926.

inal thickness. The beds above the ore dip toward it with maximum dips of 10°. They had been let down as solution occurred along the major solution plane above the ore. Possibly, the nearness of this ore body to the La Motte sandstone below was a factor in furthering the large amount of solution work accomplished, and very probably the same joints that allowed the solutions to enter permitted the removal of the dolomite. This entire stope shows abundant evidence of solution work and reconcentration of galena. Another stope in mine No. 16 shows the removal of a dolomite bed from 32 to 42 inches thick, and the concentration of the ore into a layer 7 to 10 inches thick. The solution action stopped within a distance of 6 to 8 feet (Fig. 17).

Not all the ores of the district have been reconcentrated in this way, however. Such concentrated ores are most common in the lower part of the Bonneterre. It is also possible that some ore horizons are later than the residual clay bands, the major part of the solution work having occurred prior to the ingress of the ore-bearing solutions. This, however, does not appear to have been of common occurrence, as replacement of the residual clay is rare. The ore solutions may also have been instrumental in sealing off some areas from the ground waters that subsequently entered the Bonneterre dolomite. On the whole, however, the solvent action of ground waters has improved the tenor of the ores in the district.

Corroborative Evidence.

The study of an ore deposit always reveals some lines of collateral evidence that bear somewhat upon the problem, and it is believed that a summary of such points may be of value in this study. Included will be the general mineralogy, position of the ores in geologic section, zonal arrangement, chemical data, bacteriological possibilities, fluorine in the igneous rocks, and possible significant relationships shown by other deposits.

The ore mineral aggregate is typically that formed by magmatic waters. Galena is consistently associated with magmatic ores, the world over, proving that the transportation of lead (and sulphur) is accomplished best by magmatic solutions. Cobalt and

nickel ores are not known to have been formed by meteoric waters (neither has galena, for that matter). Chalcopyrite and sphalerite are found with magmatic-solution deposits everywhere. Even marcasite is most common and abundant in hot-water deposits. The group of minerals, as a whole, is typical of magmatic-water deposition, and the presence of the dickite lends support to this view. Lindgren [61] notes that Zn is normally deposited between Cu (first) and Pb (last).

The minor metals (like the minor minerals) present in a deposit must also be regarded as significant. In this connection, a recent paper by Graton and Harcourt [62] is of more than passing interest, and has a bearing upon the origin of the southeastern Missouri lead deposits even though the authors did not examine any sphalerite from the lead belt. The paper states that the sphalerite from the Mississippi Valley ores shows "the presence of comparable quantities of the same relatively rare elements" as occur in sphalerite from generally accepted magmatic deposits. Quoting from page 801:

> We submit that this parallelism is to be interpreted as presumptive evidence of substantial similarity as to source and as to process of accumulation and precipitation for both sets of deposits. And if choice must be made between the "meteoric" and the magmatic as the single origin *for the lot as a whole*, few could now deny that the evidences in support of the fundamental validity of the magmatic origin are by far more direct and inescapable than are the evidences for a "meteoric" origin for all these ores or for any subdivision of them. Moreover, the relative quantities of these rare elements in sphalerite are found to vary serially in such manner as to be rationally explained if the Mississippi Valley type of ores constitute the low-intensity end-member of the hydrothermal group, all other subdivisions of which are now firmly established as magma-derived.

Other arguments on page 808 further support this view, and in concluding, the authors forcibly state their position as favoring a magmatic origin and say: "It is to be hoped that the meteorists

[61] Lindgren, W.: Mineral Deposits, p. 197, 1933.

[62] Graton, L. C., and Harcourt, G. A.: Spectrographic Evidence on Origin of Ores of the Mississippi Valley Type. ECON. GEOL., vol. 30, pp. 800–824, 1935.

will recognize and accept the challenge which these several recent lines of evidence constitute."

Ridge,[63] in a recent paper on the Tri-State deposits, finds that the mineralogical evidence favors a hydrothermal origin, which adds to the growing group of men who favor such an origin.

The ore bodies lie, typically, in the lower part of the Bonneterre dolomite, and if they had been formed by meteoric water, why should they not occur in the upper part, or in other carbonate rocks higher up? The reason usually cited is that the lower portions contained the precipitating agent carbonaceous matter, which has, however, been shown to be ineffective for this purpose. Repeated solution, downward movement, and final deposition, as suggested by Buckley, is a sequence so utterly out of keeping with the chemistry of lead salts as to have little importance as a theory. Under the magmatic hypothesis, the position of the ores is normal. The ore bodies occur independently of the overlying rocks (Davis shale, etc.). To have carried the lead ores down through the impervious shale would have been a somewhat difficult process.

The zonal theory has been applied to many deposits in recent years. It is of most importance here in showing that geologists have come to recognize the ability of solutions to migrate considerable distances from the source magma, and to show that physio-chemical factors influence the time, place, and mode of deposition of the ores. If the common zonal arrangement[64] is accepted, lead ores would normally be at a distance from the source magma and relatively near to the surface. The data secured in this study places the southeastern Missouri deposits among the low-temperature and remote (telethermal) deposits. Lead ores occurring alone should be nearer the surface than those associated with other metals, for lead has a great vertical range.

Virtually all lead salts are insoluble in ordinary cold solutions. When regard is paid to this factor, a theory that makes use of

[63] Ridge, John: Genesis of the Tri-State Zinc and Lead Ores. ECON. GEOL., vol. 31, pp. 298–313, 1936.

[64] Emmons, W. H.: Am. Inst. Min. Met. Eng. Trans., vol. 70, pp. 964–997, 1924. Davison, E. H.: The Primary Zones of the Cornish Lodes. Geol. Mag., vol. 58, pp. 505–512, 1921. Lindgren, W.: Mineral Deposits, pp. 119–122, 1933.

cold, weak meteoric waters to bring about the concentration of minutely scattered traces of lead into large rich ore deposits is ignoring a vital feature in the chemistry of the metal. And where the lead is associated with other metals that are normally transported by magmatic solutions (as in the Missouri deposits), the theory that the lead ore is due to magmatic solutions is greatly strengthened. Proof of the inability of meteoric waters to transport lead is shown by the common occurrence of residual deposits of galena.

The possibility that sulphate-reducing bacteria may have played some part in the formation of the ores led the writer to have samples of the ores tested for their presence. The tests were made by Professor W. A. Albrecht of the Soils Department of the University of Missouri. Professor Albrecht followed the procedure used by Bastin and his associates [65] and also used media similar to theirs, but the results were negative although samples of soil put in the same medium showed an abundance of the sulphate-reducing bacteria. These tests were made, not because the writer believed there was more than a mere chance that bacteria had played a part in the origin of the lead ores, but in order to check up on any possible line of evidence however remote it might appear to be.

Aside from the chlorides in the liquid inclusions that Newhouse found in galena (the writer, as stated, was unable to find any of these inclusions, although numerous specimens were broken in the search), the mineralogy of the ores does not in itself indicate that the lead was transported as the chloride. Neither is fluorine present in the ores. The igneous rocks of southeastern Missouri and the veins cutting the granites and the specularite iron ores all show fluorite. One vein [66] cutting the granite at Graniteville shows large amounts of fluorite along with barite and pyrite. Both the common halogens may have been present in the ore solutions, but the writer thinks that chlorine is the more likely, because not only is lead chloride the more

[65] Bastin, E. S., and others: Am. Assoc. Pet. Geol. Bull., vol. 10, p. 1288, 1926.

[66] Tarr, W. A.: Barite Vein Cutting Granite of Southeast Missouri. Am. Min., vol. 17, pp. 443–448, 1932.

soluble but it seems probable that if fluorine had been present fluorite would have formed in the presence of the calcium of the dolomite. The chlorine could easily have escaped in any one of the many soluble chloride salts. The amount of Ca-Mg removed from the dolomite during the replacement by the ores was large, and these elements, also, were doubtless removed as the chlorides.

Some traces of H_2S are reported in the water of the La Motte sandstone. It is conceivable that this gas is still rising from below, though these traces may have had an entirely different source. The matter is not regarded as significant.

Lastly, though not to be considered as corroborative evidence, foreign geologists have quite consistently regarded the deposits of southeastern Missouri as of magmatic origin. The lack of associated igneous rocks apparently had less weight with them than the mineralogy and mode of occurrence of the ores.

Summary.

The writer finds the meteoric-water hypothesis untenable in explaining the origin of the Missouri lead ores because of its inadequacy in accounting for the source, transportation, and deposition of the metals, as well as their mode of occurrence and mineralogy. He believes that the ores are of magmatic origin because magmatic solutions are a more adequate source of the metals, have the solvent ability to transport them, and meet the mineralogical requirements for their deposition. The mode of occurrence of the ores in the Bonneterre dolomite can be suitably accounted for by the lithological and structural conditions of the mineralized area, and is, moreover, fully in keeping with a magmatic source for the ores. Important new evidence bearing upon the origin and occurrence of the ores is furnished by the discovery of dickite in the deposits, and the recognition of the fact that the richness of the ores is due in large part to their reconcentration through solution of the country rock along stylolites, stylolitic seams, and other solution planes.

UNIVERSITY OF MISSOURI,
COLUMBIA, MO.,
August, 1936.

PERSPECTIVE BLOCK DIAGRAMS.

MARK H. SECRIST.

ABSTRACT

Several new ideas are presented which result not only in a quicker and simpler drawing procedure but also make possible the construction of exact, measured-to-scale perspective block diagrams instead of idealized pictures, as they now largely are. The trigonometric method is proposed, the use of which permits the entire drawing to be made in one plane—the perspective plane—hence, a simplified drawing procedure. It also permits the plotting of the several vanishing points as exact distances measured along the horizon from the center of vision instead of being points located by the intersection of two or more lines. The distances are found by means of one simple trigonometric formula. In diagrams drawn in angular perspective, two additional vanishing points, termed triangle points, are used.

It is suggested that all perspective block diagrams be accompanied by the following data: (1) the coordinates of the position of the observer's eye, (2) in angular perspective, the angle made by one of the receding edges of the block with the perspective plane, and (3) the dimensions of the block.

INTRODUCTION.

THE popularity of block diagrams is increasing in geologic publications. Up to the present time perspective block diagrams have been largely idealized drawings which, for the most part, possess little, if any, three-dimensional exactness. This deficiency is a consequence of heretofore existing difficulties in the laborious constructions necessary. Accordingly it is felt that the description of a new and simple method that permits accurate measurements, to scale, either upon or within the block, will be timely.

Block diagrams are useful as an effective means of pictorial representation in many branches of geology. Perhaps they are most useful, however, to the structural and mining geologist because his work in the field is necessarily in three dimensions and his results, in turn, gain their most impressive and convincing

clarity when they are presented as three-dimensional pictures, drawn accurately to scale. Block diagrams of the perspective type make possible the desired combination of an accurate projection and a natural appearance.

Users of the diagrams are aware of the fact that two types, namely, the isometric projection and the cabinet (cavalier) projection, are drawn entirely to scale. But the two types just mentioned are not well adapted to effective pictorialism because they take no account of perspective foreshortening and hence they are neither natural nor pleasing to the eye. The perspective type, on the other hand, is the only one which is capable of presenting more and more distant objects or vistas in natural, relative proportions.

Fundamental Definitions and Rules

Inasmuch as perspective projections are applications of descriptive geometry, a brief review of the necessary fundamentals is offered.

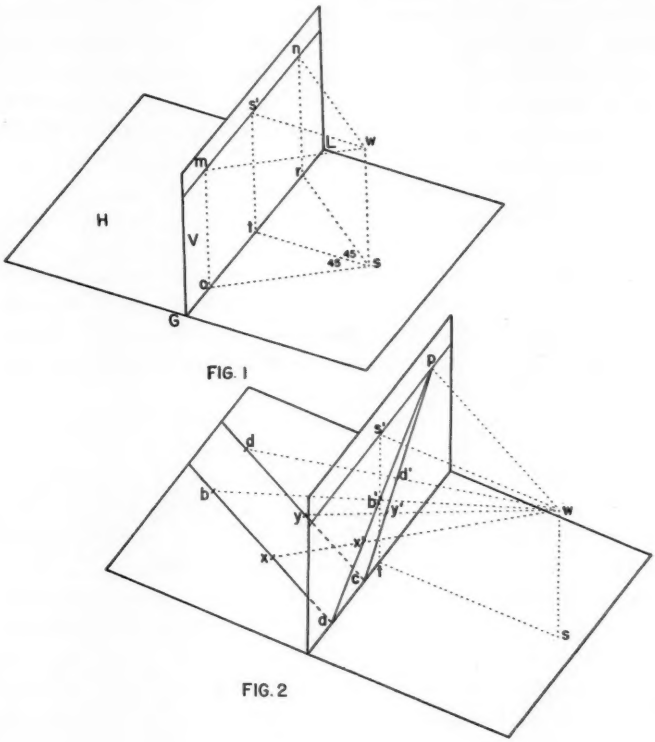
In Fig. 1 a vertical plane, V, called the *picture plane* or *perspective plane*, has been placed upon a horizontal plane, H, called the *ground plane*. Their intersection is called the *ground line*, GL.

W is the position of the eye, always in front of the perspective plane, and is termed the *point of sight*. Any line through W is called a *visual ray* and any plane containing it is called a *visual plane*. The projection of W upon the ground plane is indicated at S.

The point of sight, W, projected perpendicularly to the perspective plane, V, intersects it at S', called the *center of vision*. All visual rays parallel to H will intersect the perspective plane in the horizontal line drawn through S' and such a line is called the *horizon* ($mS'n$). The observer's eye may be considered as lying in a horizontal plane, the intersection of which with the perspective plane determines the horizon.

The perspective plane, on which the drawing is made, is considered always to lie between the eye and the object.

The convergence, on the horizon, of all receding parallel lines is a familiar phenomenon. The point of convergence is termed the *vanishing point*. Fig. 2 demonstrates the convergence of the



FIGS. 1 AND 2.

perspectives of two parallel horizontal lines at the point p on the horizon.

In Fig. 2 the lines ab and cd are two parallel lines lying in the ground plane. A visual ray from W drawn parallel to the lines ab and cd is parallel to the ground plane and intersects the per-

spective plane at p, on the horizon. Lines ap and cp lie in the perspective plane. Visual rays from W to x and b intersect the perspective plane at x' and b' respectively, which lie on line ap. Likewise, visual rays Wy and Wd cut the perspective plane respectively at y' and d' which lie on cp. Since p is the convergence point, on the horizon, of lines $ax'b'$ and $cy'd'$, it is therefore the vanishing point of the parallel lines ab and cd. Further, it is the vanishing point of all lines parallel to the latter. Hence, *the vanishing point for any horizontal line or system of parallel horizontal lines is determined by the intersection, with the horizon, of a visual ray drawn parallel to the given line, or lines.*

The horizon is the locus of the vanishing points of all horizontal lines.

A line at 90° to the perspective plane is called a *perpendicular.* A visual ray parallel to a perpendicular obviously must intersect the perspective plane at the center of vision, S' in Fig. 1. Hence, the center of vision, S′, is the vanishing point of all perpendiculars.

Horizontal lines making an angle of 45° with the perspective plane are called *diagonals.* In Fig. 1, the lines Wm and Wn are diagonals through the eye meeting the horizon. Hence m and n are the vanishing points of diagonals. The points m and n are also called *distance points* because they are as far from the center of vision, S', as the eye is from the perspective plane.

Lines parallel to the perspective plane have their vanishing points at infinity. The perspective of a vertical line is always vertical.

For the purpose of geological illustration, two types of perspective block diagrams are recognized, viz: (1) the parallel perspective (so-called one-point perspective) in which the receding edges of a rectangular parallelepiped are at 90° to the perspective plane, and (2) the angular perspective (so-called two-point perspective) in which the receding edges of a parallelepiped make angles of more than 0° and less than 90° with the perspective plane.

In parallel perspective a face of the block, the front face, lies

in the perspective plane. In angular perspective the front corner of the block lies in the perspective plane.

It is evident, from Figs. 1 and 2, that the resulting perspective picture depends upon the relative positions of (1) the object (block), (2) the perspective plane, and (3) the eye. The perspective plane is fixed with respect to the block—by convention it is usually made to coincide with the front face or front edge of the block. Hence it remains necessary to fix the position of the eye. I suggest that the lower right front corner of the block, in parallel perspective, and the front corner, in angular perspective, be adopted as the origin of coordinates, as indicated in Fig. 3 which shows the eye to be the distance X to the front, Y to the side (right), and Z above the origin.

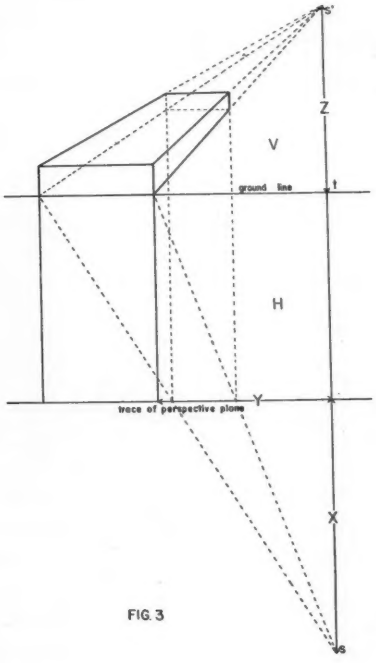


FIG. 3

Of the three coordinates necessary to fix the position of the eye, two (Y and Z) of Fig. 3 appear in true value on the perspective plane. The third (X) must be given in either one of two ways, viz: (1) by placing the horizontal projection of the eye on the H plane (as S), or (2) by placing the distance points (at least one of them) on the horizon.

A graphic method of finding the perspective picture in angular perspective is shown in Fig. 4 in which the vanishing points are four in number instead of the customary two.[1]

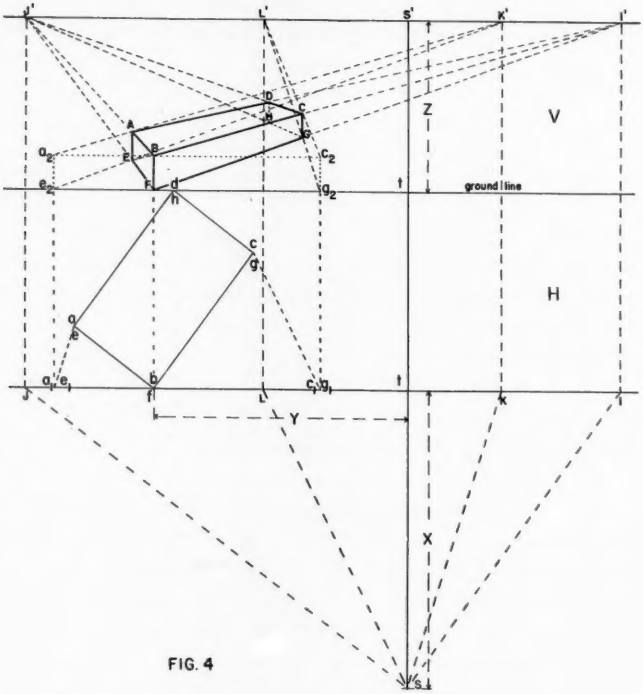


FIG. 4

[1] Lobeck, A. K.: Block Diagrams. John Wiley & Sons, Inc., pp. 22–28, 1924. Lahee, F. H.: Field Geology. McGraw-Hill, p. 606, 1931.

In the angular perspective of a rectangular parallelepiped, there are apparent two vanishing points, I' and J' (Fig. 4), since there are two sets of receding edges. These points are located by drawing line SI parallel to edge bc and line SJ parallel to edge ba. The projection of points I and J to the horizon determines the positions of I' and J'.

Two additional vanishing points, K' and L', are employed in this method. They arise from the use of the base of auxiliary isosceles triangles. The name *triangle points* is suggested for these vanishing points.

The lengths of the receding edges fg and fe are scaled off along the trace of the perspective plane as fg_1 and fe_1, respectively. Lines gg_1 and ee_1 are drawn. Triangular prisms aba_1efe_1 and bcc_1fgg_1 may be considered as auxiliary blocks. Line SL is drawn parallel to gg_1 and the vertical projection of L is L', on the horizon. L' is therefore a triangle point, the vanishing point of all lines parallel to edges cc_1 and gg_1. Similarly, K' is the triangle point for edges aa_1 and ee_1.

On the V plane the receding faces are plotted to scale in elevation as a_2e_2BF and c_2g_2BF. The perspective positions of the corners A, E, C, G, D, and H are then determined by the intersections of lines drawn to the proper vanishing and triangle points.

THE PROPOSED TRIGONOMETRIC METHOD.

In order to simplify the construction of perspective block diagrams, the following procedure is offered. Its advantage is that all constructions are made in the perspective plane. A simple trigonometric formula is used to locate the necessary vanishing points on the horizon (three in parallel perspective and four in angular perspective).

In the following discussion the angle that a receding edge makes with the positive direction of the Y-axis is designated by α and is always measured counter-clockwise from the Y-axis (ground line).

Figure 5 is a plan drawing showing the projection of the eye as point S; the trace of the perspective plane as I_4I_1; the projec-

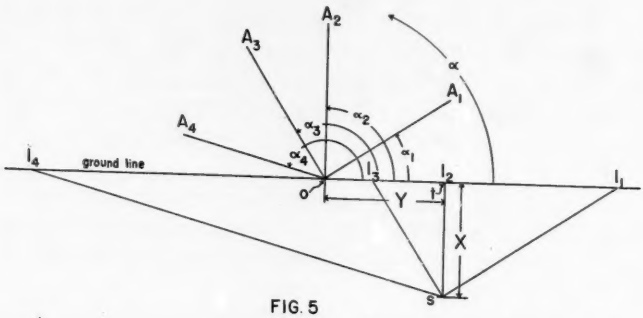


FIG. 5

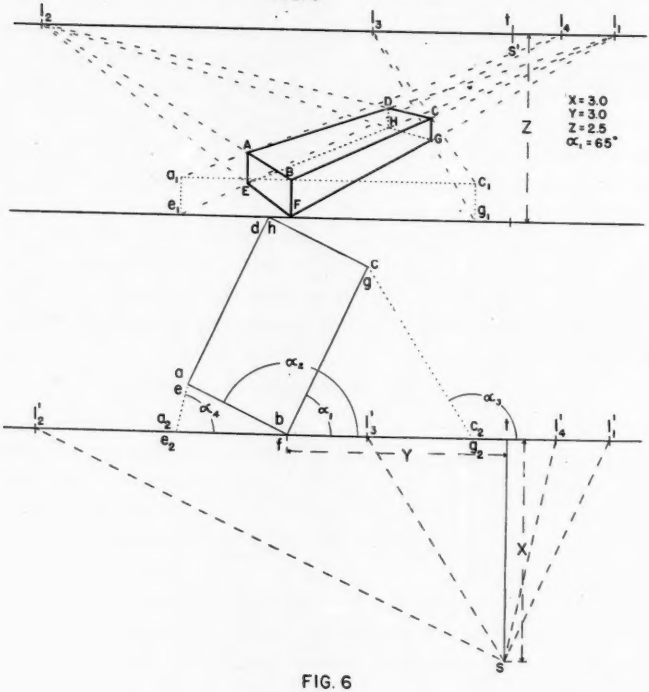


FIG. 6

FIGS. 5 AND 6.

tion of the center of vision as t; the projection of the front edge of the block as point O; the projections of the receding edges of blocks placed at various angles α_1, α_2, α_3, and α_4 as OA_1, OA_2, OA_3, and OA_4, respectively. The position of the eye in plan is indicated by its coordinates X and Y.

Lines SI_1, SI_2, SI_3, and SI_4 of Fig. 5 are drawn parallel to OA_1, OA_2, OA_3, and OA_4, respectively, in accordance with the fundamental principle for the location of vanishing points on the horizon stated at the beginning of this paper.

The location of the vanishing point of any receding line with respect to the center of vision may be determined from the formula:

$$tI = X \text{ cotangent } \alpha$$

in which tI is the distance between the vanishing point, I, and point t, the projection of the center of vision, or from S', the center of vision. In this formula each quantity includes its sign.

The position of the vanishing point I with respect to t and O will now be discussed.

Since the eye is in front of the block, X is positive.

If $\alpha < 90°$, $\cot \alpha > 0$ and I lies to the right of t.

If $\alpha = 90°$, $\cot \alpha = 0$ and I coincides with t.

If $\alpha > 90°$, $\cot \alpha < 0$, and $\cot \alpha = -\cot (180° - \alpha)$

- if $(180° - \alpha) > \text{arc cot } \frac{Y}{X}$, then I lies between t and O;
- if $(180° - \alpha) = \text{arc cot } \frac{Y}{X}$, then I coincides with O;
- if $(180° - \alpha) < \text{arc cot } \frac{Y}{X}$, then I lies to the left of O.

In Fig. 5 the above positions for values are shown as follows:

$\alpha_1 < 90°$, accordingly I_1 lies to the right of t;

$\alpha_2 = 90°$, accordingly I_2 coincides with t;

α_3 and $\alpha_4 > 90°$, accordingly I_3 and I_4 lie to the left of t;

$(180° - \alpha_3) > \text{arc cot } \frac{Y}{X}$, accordingly I_3 lies between t and O;

$(180° - \alpha_4) < \text{arc cot } \frac{Y}{X}$, accordingly I_4 lies to the left of O.

Construction Necessary in the Trigonometric Method.

Fig. 6 shows the construction necessary to draw a rectangular block in angular perspective, using the following data: $X = 3.0$, $Y = 3.0$, $Z = 2.5$, and $\alpha_1 = 65°$. The dimensions of the block are given by the elevation projections.

In practice the plan portion of the figure is unnecessary. It has been included in this drawing only for the purpose of making clear the positions of the angles α_1, α_2, α_3, and α_4. It will be noticed that the plan portion of Fig. 6 is similar to that of Fig. 4.

The computation of the angular values follows.

$$\alpha_1 = 65°,$$
$$\alpha_2 = 90° + \alpha_1 = 155°,$$
$$\alpha_3 = 180° - \tfrac{1}{2}(180° - \alpha_1) = 122\tfrac{1}{2}°,$$
$$\alpha_4 = \frac{180° - (180° - \alpha_2)}{2} = 77\tfrac{1}{2}°,$$

from which, according to the formula $tI = X \cot \alpha$:

$$tI_1 = X \cot \alpha_1 = 3 \cot 65° = 1.399,$$
$$tI_2 = X \cot \alpha_2 = 3 \cot 155° = 3(-\tan 65°) = -6.433,$$
$$tI_3 = X \cot \alpha_3 = 3 \cot 122\tfrac{1}{2}° = 3(-\tan 32\tfrac{1}{2}°) = -1.911,$$
$$tI_4 = X \cot \alpha_4 = 3 \cot 77\tfrac{1}{2}° = 0.665.$$

Using the trigonometric method, whether the drawing be in parallel or in angular perspective, only that part which appears in the V plane (as shown in Fig. 8) is required—hence the simplicity of the method.

At the beginning of this paper it was stated that the position of points within the block could be plotted if the block be drawn to scale. Fig. 7 shows the plan and the front and side elevations of the block. The corner F is taken as the origin. The edge FG is the *x-axis,* the edge FE is the *y-axis,* and the edge FB is the *z-axis.*[2] Point W lies within the block.

Problem 1.—To find the perspective of the point W given by its coordinates x, y, and z with respect to the corner F of the block.

[2] Note—these axes, x, y, and z, have no connection with X, Y, and Z used to designate the position of the eye.

The Method.—The point W is to be considered as the intersection of two straight lines parallel to the x and y axes. Its perspective will be found at the intersection of the perspectives of these two lines.

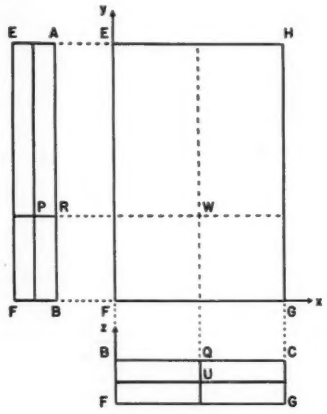


FIG. 7.

The points P' and U', in which these two lines intersect the yz and xz planes (vertical faces of the block), are taken as auxiliary points. Their perspectives, P and U, are first determined (Fig. 8) at the intersections of vanishing lines to I_4 and I_3 (triangle points) and verticals.

The perspectives being found, the perspectives of the two lines are drawn, PI_1 and UI_2 (by joining to the vanishing points of the receding edges), and their intersection W is the required point.

In Fig. 8, plot x to the right of F and y to the left. Erect verticals to R' and Q'. On each of these verticals plot z. This gives P' and U'.

Find perspective R of R' at the intersection of edge BA with the vanishing line $R'I_4$ to triangle point I_4. Find perspective P of P' at the intersection of the vertical RP with the vanishing line $P'I_4$ to the same triangle point. Find U in like manner.

Join perspectives P and U to the vanishing points I_1 and I_2, respectively, of the x and y axes (receding edges). The required perspective W is at their intersection.

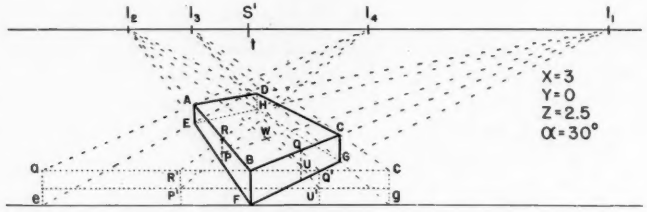


FIG. 8.

Problem 2.—A point being given in perspective, to find its location in the block.

This problem does not admit of any solution in the general case. This is due to the fact that any given point on the perspective plane is the perspective of all the points on the visual ray that intersects the perspective plane at that point.

The problem is solved easily, however, in some particular cases. For instance, for a point located on one of the faces of the block. This is of special interest in the case of structural block diagrams. Any cross section drawn on a front receding face of the block, or within the block, can be resolved into its true magnitude by joining the perspective points to the corresponding triangle points, using vertical planes as auxiliaries.

A stereo-block diagram drawn according to the methods described is shown in Fig. 9.

CONCLUSIONS.

The originality of the proposed method lies chiefly in, (1) the use of a simple trigonometric formula for the quick and accurate location of all vanishing points, and (2) in the choice of the pairs of vanishing lines (*i.e.*, the receding edges of the block and the bases of auxiliary isosceles triangles) whose intersection lo-

cates the perspective of any point—for example, a corner of the block.

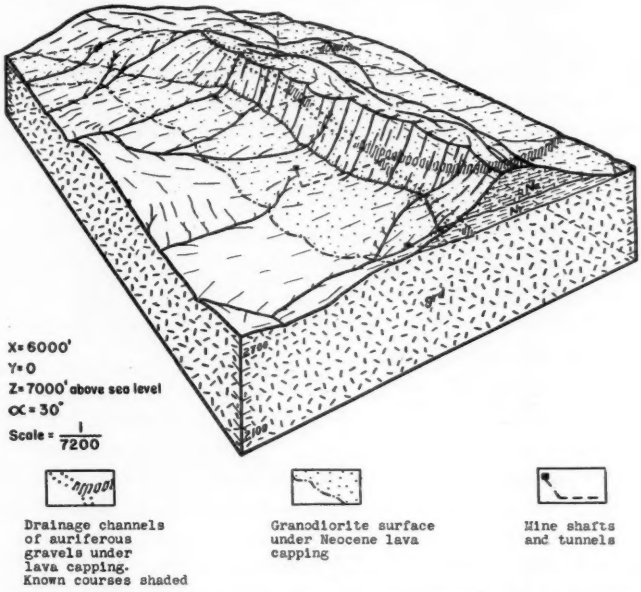

X = 6000'
Y = 0
Z = 7000' above sea level
α = 30°
Scale = 1/7200
Drainage channels of auriferous gravels under lava capping. Known courses shaded
Granodiorite surface under Neocene lava capping
Mine shafts and tunnels

FIG. 9. Stereo-block diagram, in angular perspective, of the Harmony Ridge gold mining district, California, showing the position of Harmony Channel in relation to the topographic and geologic features of the region. Diagram constructed to scale, using the trigonometric method, from the northwest corner of the Banner Hill Special Map. (Nevada City Special Folio, California, No. 29, 1896, U. S. G. S.)

The advantages of the trigonometric method over the graphic are:

1. Accurate plotting of vanishing and triangle points as distances measured from the center of vision.
2. Elimination of errors arising from carrying parallel lines.
3. Entire drawing made in the perspective plane only, hence the elimination of many construction lines.

4. Resolution of a block diagram, in which the required data (summarized below) have been given, into accurate plan and elevation projections.

Regardless of the method of construction used, it is suggested that the following data accompany every perspective block diagram so that such drawings may have accurate and quantitative values instead of remaining largely idealized, pictorial representations, as most of them now are:

1. The coordinates of the position of the eye.
2. In angular perspective, the angle made by one of the receding edges with the perspective plane, if the block be a rectangular parallelepiped.
3. The dimensions of the block (arbitrary).

JOHNS HOPKINS UNIVERSITY,
BALTIMORE, MD.,
November 4, 1936.

DISCUSSION AND COMMUNICATIONS

ORIGIN OF ANHYDRITE CAP ROCK.

Sir: Doctor Hanna's lucid presentation in your September-October issue of my interpretation of the origin of the anhydrite cap rock of salt domes has brought home to me a defect in my presentation which has resulted in the only misinterpretation in his review. He says on page 643:

> He considered the ways in which the bedded anhydrite may have become brecciated, *i.e.* (1) intraformational brecciation in the original salt series, (2) brecciated at the katatectic surface, (3) or in the flowage in the salt stock. He eliminates the former, but is unable to determine whether the second or third was the cause.

I can see various shortcomings in my presentation that have led to this misunderstanding and shall appreciate it if you will give me the opportunity through your journal to correct them.

The three types of origin of the breccia fragments that I consider are (1) intraformational brecciation, (2) brecciation, as a result of the upward movement of the salt stock, of a bed of anhydrite that overlay the sedimentary salt beds of the stock, before their upward movement, (3) brecciation, either within the salt stock or at the salt table, of beds of sedimentary anhydrite included in the salt at the time of its deposition. By residual accumulation on the salt table these last enter the cap rock. As Doctor Hanna says, I reject the first hypothesis. I reject the second hypothesis essentially because of what I have called the katatectic bands, the argument being that the brecciation of an overlying bed of anhydrite would have taken place in a single stage and that what I have called katatectic surfaces could, in that case, be the result of shearing only. As I present arguments to show that they are not the result of shearing, the third hypothesis is the only one that is left.

MARCUS I. GOLDMAN.

WASHINGTON, D. C.,
October 12, 1936.

REVIEWS

Economic Geology of Mineral Deposits. By ERNEST R. LILLEY. Pp. x + 811, figs. 301. Henry Holt & Co., New York, 1936. Price $5.00.

In these busy days, with the arts of distribution so perfected that worth may not determine sales, the book review should serve as a protecting classifier to dispose of tailings or middlings and retain for the serious consumer only the valuable concentrates. In a relatively small and specialized scientific field, where personal acquaintance is wide-spread, the critic is inclined to deal gently; yet if wholly objective appraisal were happily universal, suspicion of animus behind plain words would be rare. The book in hand deserves no harsher criticism than many another; but to some degree it exemplifies a tendency toward easy standards against which it is here made the vehicle for protest.

The purposes of this large, good-looking volume, as avowed in the preface, are to emphasize the close relationship between geological factors and economic values, to improve understanding of the interdependence existing between mineral resources and the world's commerce and industry, and thus fill the need of a text embodying the basic fundamental facts and principles of such relationship and interdependence. The author has never lost sight of these worthy objects. Indeed, the book's value must be judged almost wholly by these geologico-economic standards, since the contribution to an understanding of economic geology or mineral deposits *as such* appears quite inadequate to justify a new book in that well-covered field.

The *economic* aspects of mineral deposits are mainly those which can be handled statistically, *i.e.*, by dates, quantities, trends, etc.; the authorities used are recent and accessible. This material, offered as the "fundamental facts," is so interwoven as to be in considerable degree submerged in a running account of geological items of a descriptive kind assembled from the better-known literature. Occasional brief glimpses toward a philosophy of mineral finding and use fade undeveloped. Of "fundamental principles," whether economic or geological, the final chapter of 10 pages contributes most.

The publishers offer this as a comprehensive text for the second-year course in geology. The student would gain much that is informative, but would not be greatly strengthened in reasoning power, scientific ap-

preciation, or grasp of geological processes and their consequences. The book thus seems ill-suited for those who plan to continue the study of geology and especially economic geology. It might serve as collateral reading for a student in economics or business after one introductory geological course; or for any person who desires mineral statistics with a more geological flavor than is found in, say, "Mineral Industry" or "Minerals Year Book." Even for these purposes the book is too long. The arrangement, which joins things of like use or like price rather than primarily of like natural occurrence, is not frugal of space when the discussion of geology so preponderates over economics. And with the treatment so largely factual and descriptive, duplication results under each major heading from including a generalized introduction before the more specific comment.

For a first edition, the errors are not unduly numerous. Nor are they flagrant, but rather of that subtle kind which comes from knowing the words without quite getting the tune, like Mrs. Mark Twain's synthetic profanity. Their nature may be indicated by a few examples selected from those general topics most familiar to the reviewer. It seems certainly a step toward loose usage to suggest (pp. 3–4) such definition of "ore" as would make "ore deposit" refer to *any and all* mineral occurrences that can be worked at a profit regardless of whether metal is produced. "Protore" (p. 6) is distorted from Ransome's etymologically appropriate definition; but the author is not the first offender here. The "average" vein of copper (p. 10) is ascribed a present-day tenor of "possibly between five and six per cent"! Though phrased as a general conclusion (p. 13), it must be only occasionally that the value of an ore depends as much on nature of gangue as on metal content. Of the epithermal gold deposits it is stated (p. 564) that the values are largely localized in non-persistent lodes (sic!) within the veins. Readers more capable than the reviewer of appraising the treatment of non-metals may conclude that those parts of the book are better. But the author freely chose his scope, so must bear responsibility for the whole.

Each major section is followed by a selected bibliography. Most of the standard modern works in English are included, and some titles of minor rank. For illustrations, statistics and tabular material full acknowledgment is given. But the countless assertions of the text rest on only about 25 citations to the literature. This short-cut for the author is at the expense of the serious reader, besides being thoroughly bad for those in "the second year course in geology."

The style is straightforward and pleasing; ambiguity is impossible save where the author, too, appears to have been uncertain. The printing is excellent except through insufficient variety of types for logical ranking of headings. The plentiful illustrations are commendably clear and

crisp. Many of them pertinently amplify the text; others, including notably the mine maps, do not. There is an adequate index.

This cannot be regarded, then, as a weighty contribution to the field it undertakes to cover. It contains much information, most of it reliable and well presented, but of which by far the greater part is available in single texts that treat the geological considerations more scientifically and satisfactorily. Lacking is the insight that comes only from long field experience, and the sparkle that emanates only from the rare master. As for economic data, the book does assemble a kind and amount not equalled in these other texts, nor perhaps existing between any one pair of covers. But the value of this assembly is considerably lessened because these data constitute so disseminated a part of the book, and are of a nature not conducive to profound handling.

L. C. GRATON.

LABORATORY OF MINING GEOLOGY,
HARVARD UNIVERSITY,
CAMBRIDGE, MASS.

India's Mineral Wealth. By J. C. BROWN. Pp. x + 335, pl. 8, maps 6. Oxford University Press, 1936. Price $5.00.

Although no indication of the fact appears on its title page, this is the second edition of the book with the same title that was published in 1923. It has been entirely rewritten and enlarged, primarily with the object of "drawing attention to the commercial and industrial potentialities that the mineral deposits possess in the hope that capital and enterprise will be forthcoming for their further development." Its appearance is timely because of the great increase in India's rapid development of its mineral industries within the past decade. The present volume gives "detailed and up-to-date information of all the important minerals of India and Burma, their occurrences, uses, production and economics generally, with short accounts of the mining and metallurgical industries based upon them." It describes in considerable detail the great ore fields of Bihar and Orissa, the copper district in Bihar, the complex silver-lead ores in the Federated Shan States, the great wolfram deposits of Lower Burma, the valuable beach sands of Travancore, and the well known mica and manganese deposits, as well as the metallurgical and other industries dependent upon them.

Each useful mineral that India produces is considered individually, its chief occurrences are discussed and the history of its commercial exploitation is outlined. Moreover, brief references are given to the occurrences of minerals that have not yet been found in large enough quantities to be of commercial importance and the localities at which they are known to be present are indicated. The geological environment of

each occurrence is described and a brief sketch of its method of origin is given.

The products dealt with in greatest detail are petroleum, iron, gold, lead, zinc, tin, manganese, magnesite, potash and sodium salts and gem stones, though many others are treated briefly, among them chromite, molybdenum, tungsten, antimony, arsenic, bismuth, various clays, barite, ilmenite, corundum, garnet, kyanite, sillimanite, graphite and beryl.

An appendix contains the statistics of the country's mineral production in 1933 and 1934.

The book is clearly written in concise language and apparently covers its subject as thoroughly as is possible in a volume of its size.

W. S. BAYLEY.

Geology of the Tampico Region Mexico. By JOHN M. MUIR. Pp. 280. Amer. Assoc. of Petrol. Geol., Tulsa, Okla., 1936. Price $4.50.

This volume presents a complete summary of existing knowledge of the geology of northeastern Mexico. It is not merely a compilation of the work of numerous other geologists, but rather a selective presentation of the choicest and most trustworthy data as interpreted by one who has worked in the region for many years and furthermore has taken an active part in building up the store of information.

The introductory chapter consists of an interesting account of the early history of geologic investigation and especially of the reports on oil indications. Part II is devoted to stratigraphy and paleontology. It is exceedingly well done and furnishes the reader with a precise and most detailed picture of the nature of the rock sequence. The author has been careful to incorporate original descriptions of formations and to trace the changes which have led up to present interpretations. Many columnar sections, cross sections of particularly informative areas, and maps, aid greatly in making this part entertaining and readily digestible. Of special interest is the story of the gradual evolution of ideas regarding the main producing horizons of the Tampico region. Paleontologists will be pleased with the rather full lists of fossil forms given for each formation.

Part III is devoted to igneous rocks and to seepages. Since both are particularly numerous in the Mexican oil fields, the reader will find this chapter of value. He will be interested in the relationship between igneous intrusions and seepages as well as in the diversity of igneous types found. The last part of the book is given over to a discussion of the structural features of the whole area and the structure of the oil fields in particular. After presenting an illuminating summary of the tectonics of the mountains, the plains and the framework of the oil fields, Muir gives the reader a detailed description of the structural peculiarities and

characteristics of each of the two fields. Here will be found some ideas original with the author and some that represent the cumulative influence of years of close observation. This applies particularly to the so-called Northern Fields. It will be recalled that not only the largest gushers of the world were found in Mexico but also wells which have yielded the largest individual total production. The explanation of the character of the reservoirs and the origin of the structural traps is therefore of outstanding interest.

An appendix gives data on oil field temperatures, well pressures, shooting and acid treatment, and miscellaneous stratigraphic data. It is followed by a bibliography, a list of reference maps, a gazetteer and index.

To the geologist who, like the reviewer, has spent a number of years in the Mexican oil fields, this book will appear remarkable because of the surprising amount of information accumulated during the last decade. In 1922 the stratigraphy was known only in skeleton form and the paleontology was practically unknown; the Tamasopo limestone was the producing horizon and the structure was only surmised. Now the stratigraphy is not only clear, but the horizontal facies changes are known from east to west and north to south. The imposing array of microfossil lists indicates the refinement introduced into the study of well cuttings, which fifteen years ago were not even collected.

With the rapid approach of the day when the oil fields of the United States will no longer suffice to supply our needs, attention will be focused on Mexico. This labor of love on the part of Mr. Muir will then become an indispensable foundation for exploratory work. The oil fraternity will also have occasion to express its gratitude to the American Association of Petroleum Geologists whose support has made the volume possible.

W. A. VER WIEBE.

UNIVERSITY OF WICHITA,
WICHITA, KANSAS.

Geology of the South and Southeastern Parts of the Musoma District. By G. M. STOCKLEY. Pp. 48. Colored maps. Tanganyika Geol. Surv. No. 13, 1936. Price, 4/–.

An area near Lake Victoria with pre-Cambrian basement volcanics, banded ironstones, granites, lamprophyres, bostonites, dolomites, norites, gabbros, and altered Paleozoic sediments and Tertiary volcanics.

Gold mineralization is associated with the younger granite in the form of pyritic quartz reefs, some of which have undergone either residual or secondary enrichment by solution and redeposition through the agency of lateritic manganese. Blende, galena, chalcopyrite and some arsenopyrite also occur. Eleven mines and prospects are described. 9365 ozs. of gold were produced in 1934.

BOOKS RECEIVED.

J. D. BATEMAN.

Geology and Ground-Water Resources of the Elizabeth City Area, North Carolina. S. W. LOYMAN. Pp. 57, pls. 4, figs. 5. U. S. Geol. Surv. W–S. P. 773–A, 1936. Price, 10 cts. Geology; drill cores; possible ground-water supply adequate for Elizabeth City.

Labelle-L'Annonciation Map-Area. F. F. OSBORNE. Pp. 52, pls. 8, figs. 6, maps 2. Quebec Bur. of Mines, Ann. Rept., Part E., 1934 (1935). Typical Laurention Area on projected road from Montreal to Abitibi; deposits of garnet, graphite, lime, ochre, and other non-metallics.

Geology of the Salt Valley Anticline and Adjacent Areas, Grand County, Utah. C. H. DANE. Pp. 184, pls. 19, figs. 4, maps 3. U. S. Geol. Surv. Bull. 863, 1935. Price, $1.00. Stratigraphy from Carboniferous to upper Cretaceous; details of anticlines, synclines, grabens, domes, and fault zones; salt flowage; oil, gas, gypsum, salt, uranium, and vanadium ores. Excellent photographs.

Water Resources of Edwards Limestone, San Antonio Area, Texas. P. LIVINGSTON, A. N. SAYRE, AND W. N. WHITE. Pp. 52, pls. 1, figs. 4. U. S. Geol. Surv. W–S. P. 773–B, 1936. Price, 10 cts. Investigation to determine capacity of San Antonio artesian reservoir with a view to maximum water withdrawal without serious depletion of supply; greater withdrawal is possible.

Geology of the Coastal Plain of South Carolina. C. W. COOKE. Pp. 196, pls. 16, figs. 2, maps 2. U. S. Geol. Surv. Bull. 867, 1936. Price, 60 cts. Coastal terraces; stratigraphy; Upper Cretaceous to Pleistocene; description of phosphate, lime, marl, clay, kaolin, sand and gravel, and ground-water.

Book Cliffs Coal Field, Emery and Grand Counties, Utah. D. J. FISHER. Pp. 104, pls. 6, figs. 2, maps 9. U. S. Geol. Surv. Bull. 852, 1936. Price, 75 cts. Stratigraphy: Cretaceous to Quarternary; structure; descriptions of oil and gas and bituminous coal beds.

History of the Upper Mississippi River in Late Wisconsin and Postglacial Time. WM. S. COOPER. Pp. xii + 116, figs. 44, pls. 4. Univ. of Minnesota Press, Minneapolis, 1935. Price $4.00. A study of the development of the present drainage pattern of the Upper Mississippi. It furnishes a rather complete and detailed account of the changes in the courses of the Upper Mississippi and its branches since the beginning of the withdrawal of the late Wisconsin glacier, and the production and development of the associated sand dunes.

SCIENTIFIC NOTES AND NEWS

N. H. Darton, of the U. S. Geological Survey, Washington, D. C., has completed a map showing the structure of the northern anthracite coal basin, Wilkes-Barre, Pa., by 100-ft. contour lines on the lowest coal bed.

John Payne, Jr. has returned from Bolivia, resigning his position as chief geologist for Patiño Mines & Enterprises, and is now living at 904 Park Road, El Paso, Texas.

D. R. Grantham, Director of the Geological Survey, British Guiana, is in England on leave.

Lawrence B. Wright and Samuel H. Dolbear announce the organization of the firm of Wright, Dolbear & Company, Ltd., consulting mining engineers and geologists, with offices at 17 Battery Place, New York City. H. Foster Bain will be associated with the firm.

George H. Ashley gave an address on "The Emergence of Ideas as Illustrated from Geology" at the November meeting of the Washington Academy of Sciences.

John B. Lucke has resigned from the Soil Conservation Service to join the faculty at West Virginia University, Morgantown, West Virginia, where he is assistant professor of geology.

R. Van A. Mills, formerly chief petroleum engineer for the Continental Oil Company, has been made proration engineer.

The Society of Economic Geologists will meet with the section on Mining Geology of the American Institute of Mining and Metallurgical Engineers at the February meeting in New York City. It is hoped to arrange a symposium on the Relations of Mine Subsidence to Geology, and Dr. E. L. Bruce will lead a discussion on the localization of ore bodies. Papers on the above subject, or any subject applying to Economic Geology, will be gladly received. Titles from members of the Society of Economic Geologists may be sent to G. M. Schwartz, Department of Geology, University of Minnesota, Minneapolis, Minnesota. Titles from members of the Institute may be sent to G. M. Fowler, Joplin National Bank Building, Joplin, Missouri.

C. W. Wright recently made a brief trip to Norway and Sweden. His official headquarters in Europe have been moved from Berlin to the American Consulate in Vienna, Austria.

Arthur Notman is expected back from Africa on Dec. 15th.

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